

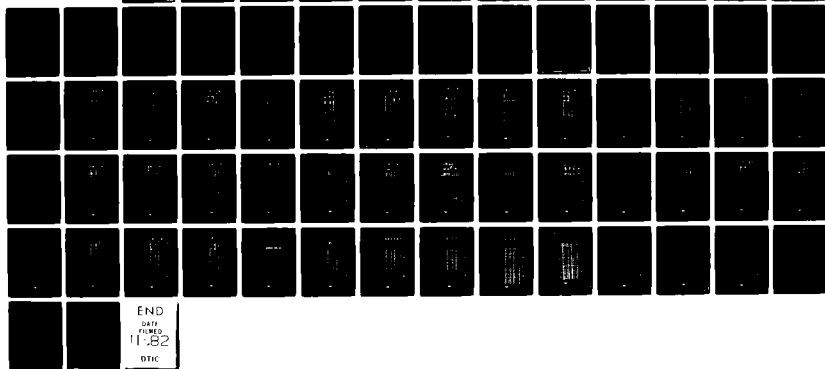
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COATINGS AND CATHODIC PROTECTION OF PILING IN SEAWATER: RESULTS--ETC(U)
AUG 82 J BUKOWSKI, A KUMAR
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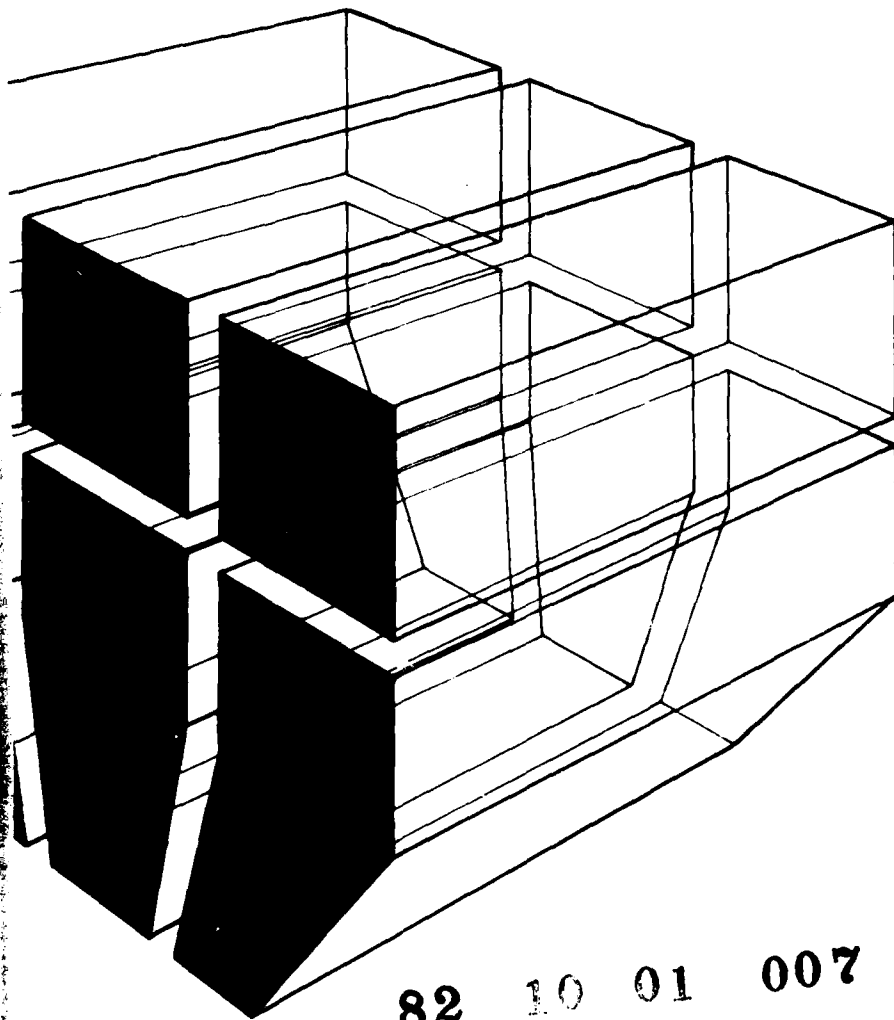
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TECHNICAL REPORT M-321
August 1982

COATINGS AND CATHODIC PROTECTION OF PILING
IN SEAWATER: RESULTS OF 10-YEAR EXPOSURE
AT LACOSTA ISLAND, FL



by
J. Bukowski
A. Kumar

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The objective of this study was to assess (1) the rate of corrosion of bare steel with and without cathodic protection, and (2) the effectiveness of various commercially available coating systems in preventing corrosion of steel piles in seawater at LaCosta Island, FL. Included were 25 coatings and four sacrificial anode cathodic protection systems.		

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→ Twenty-nine (two piles per set) American Society for Testing and Materials (ASTM) A36 or ASTM 690 steel H-piles were exposed for 10 years. Most of the piles were coated or had cathodic protection. In 1981, the piles were pulled out and inspected visually. Performance ratings were then established for the following coatings: organic, metal-filled, organic over metal-filled, metallic, organic over metallic, and organic with cathodic protection.

Based on this study, the following conclusions were drawn:

1. The corrosion rates—determined by flange thickness measurements in the immersion zone—were 7 and 6 mils (0.18 and 0.15 mm) per year respectively for bare carbon (A36) and mariner (690) steel. Sacrificial zinc or aluminum anodes effectively reduced the corrosion in the immersed zone to less than 0.1 mil (0.003 mm) per year. (Adding sacrificial anodes to a coated steel piling also protects steel in the immersed zone if the coating is damaged.)

2. A polyester glass flake coating (System 29) was the top performer. Epoxies over zinc-rich primers (Systems 20, 10, and 18) and vinyl-sealed, flame-sprayed aluminum and zinc (Systems 14 and 16) coatings performed very well after 10-years' exposure.

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FOREWORD

This investigation was conducted for the Directorate of Civil Works, Office of the Chief of Engineers (OCE) under CWIS 31204, "Corrosion Mitigation in Civil Works Projects." Mr. J. Robertson, DAEN-CWE-E, was the OCE Technical Monitor.

The work was performed by the Engineering and Materials Division (EM) of the U.S. Army Construction Engineering Research Laboratory (CERL). Dr. R. Quattrone is Chief of EM.

Appreciation is extended to CERL personnel who participated in the inspections: Mr. C. Hahin, Mr. F. Kisters, Mr. J. Aleszka, Ms. R. Hannan, Mr. W. Gordon, and Mr. F. Kearney.

COL Louis J. Circeo is Commander and Director of CERL, and Dr. L.R. Shaffer is Technical Director.

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COATINGS AND CATHODIC PROTECTION OF PILING IN SEAWATER: RESULTS OF 10-YEAR EXPOSURE AT LACOSTA ISLAND, FL

1 INTRODUCTION

Background

The Directorate of Civil Works, Office of the Chief of Engineers, has jurisdiction over many coastal structures such as bridges and buildings which are supported on pilings. The design life of these structures can range from a few years to 100 years. Steel pipes and steel H-piling have been used most often for foundations in coastal areas, but prestressed concrete piles also have been tried.

Coating systems are available to protect steel piling. And in brackish water or saltwater applications, where the life of even the best available coatings can be somewhat limited, cathodic protection can provide supplemental protection. In addition, the chemical industry continually develops new coatings which may be used in seawater. Zinc-rich primers and flame-sprayed metallic undercoats can also improve the performance of coating systems.¹

The designers of coastal structures can choose from many protective coating systems for steel piling. For rapid screening of these coatings and primers, nondestructive measurement techniques capable of predicting long-life (50-year) performance based on tests of shorter duration are extremely valuable. However, such tests performed in the laboratory, though indicative of coating performance, do not simulate actual field exposures. Field tests at various geographic locations are necessary because environmental effects such as marine growth, temperature, and tidal conditions are important parameters which cannot be simulated easily in the laboratory.

In response to this problem, the U.S. Army Corps of Engineers and the National Bureau of Standards (NBS) began a field study of piling corrosion in 1967, when 31 sets of piles (three identical piles per set) were

installed near Dam Neck, VA. Every 5 years, one row of piling was to be extracted and examined for corrosion damage; all piles have now been removed and are being evaluated by NBS.

To determine the effects of geography and temperature, the Coastal Engineering Research Center (CERC) selected two more sites, Buzzards Bay, MA, and LaCosta Island, FL. The U.S. Army Construction Engineering Research Laboratory (CERL) was responsible for installing piling at Buzzards Bay in October 1974, and conducted the first inspection in July 1975.² Annual inspections of the piles have been conducted since then.³ The first set of piling was extracted in 1979 and evaluated.⁴ The Buzzards Bay phase of the study will be completed in 1989.

The installation of 31 sets of piling (three per set) at LaCosta Island was completed in January 1971, and inspections have been conducted since then. CERC evaluated the pilings through June 1974, when the inspection responsibility was transferred to CERL. One row of piling was removed in 1976; the results of the 5-year inspection have been previously published.⁵ The LaCosta Island piles were extracted and evaluated in 1981, as this report explains.

When the Dam Neck, Buzzards Bay, and LaCosta Island studies are finished, the data from all three sites will be analyzed to draw conclusions and develop recommendations about pile coatings.

Objective

The objective of this report is to assess (1) the rate of corrosion of bare steel with and without cathodic protection, and (2) the effectiveness of various commercially available coating systems in preventing corrosion of steel piles in seawater at LaCosta Island, FL.

²A. Kumar and C. Hahn, *First Annual Inspection of Buzzards Bay Pilings*, Technical Report M-172/ADA024381 (CERL, 1976).

³F. Kearney, *Corrosion of Steel Pilings in Seawater: Buzzards Bay-1975-1978*, Interim Report M-275/ADA078626 (CERL, 1979).

⁴A. Kumar, R. Lampo, A. Beitelman, *Corrosion Control of Pilings in Seawater: Buzzards Bay*, Technical Report M-286/ADA097086 (CERL, 1981).

⁵A. Kumar and D. Wittmer, "Coatings and Cathodic Protection of Pilings in Seawater: Results of 5-Year Exposure," *Materials Performance*, Vol 18, No. 12 (1979), p 9-19.

¹A. Kumar and D. Wittmer, "Coatings and Cathodic Protection of Pilings in Seawater: Results of 5-Year Exposure," *Materials Performance*, Vol 18, No. 12 (1979), p 9-19.

Approach

Twenty-nine sets (two pilings per set) of American Society for Testing and Materials (ASTM) A36 or ASTM 690 steel H-piles were exposed in seawater for 10 years. Most of the piles were coated or had cathodic protection. The piles were pulled out and inspected visually. CERL then established performance ratings for the following coatings: organic, metal-filled, organic over metal-filled, metallic, organic over metallic, and organic with cathodic protection.

Mode of Technology Transfer

The information in this study will be incorporated into Corps of Engineers Guide Specification CW-09940, *Painting: Hydraulic Structures and Appurtenant Works*; Technical Manual (TM) 5-811-4, *Electrical Design: Corrosion Control*; and Engineer Manual (EM) 1110-2-3400, *Painting: New Construction and Maintenance*.

2 LACOSTA ISLAND FIELD STUDY

Test Site

Figure 1 shows the LaCosta Island test site. The yearly surface water temperature ranges from 55° to 90°F (13° to 32°C), with an approximate mean yearly temperature of 75°F (24°C). The salinity fluctuation due to tidal flushing at the site is approximately 30 parts per thousand at low tide to 36 parts per thousand at high tide. Mean tide level at the site is 1.3 ft (0.4 m), with a spring tide range of 2.6 ft (0.8 m). Wave action is light, and the bottom material is composed of approximately equal proportions by weight of silica sand and shell.⁶

Test Piling

The test piles included H- and pipe-piling made of either American Society for Testing and Materials (ASTM) 436 or ASTM 690 (mariner steel). The steel H-piles were 6 in. x 6 in. x 30 ft (152 mm x 152 mm x 9.2 m) and weighed 25 lb/ft (37.2 kg/m). Stainless steel rods were welded between the inside flanges of each pile so that electrical contact could be made for electrochemical measurements. The piles were

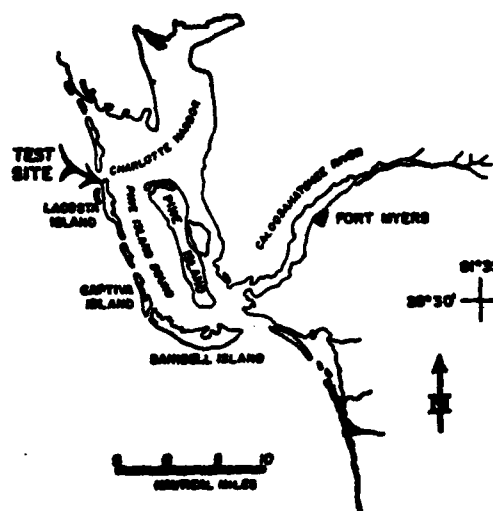


Figure 1. LaCosta Island test site (metric conversion factor: 1 nautical mile = 1.852 km).

identified by raised weld beads near the top. Six prestressed concrete piles were also installed.

Figures 2 and 3 show the detail sections of the H- and pipe-piling. Some piles were installed without coatings or sacrificial anodes, while others had both coatings and cathodic protection. Table 1 is a complete listing of the coatings used and their sources. Some of the protective coating systems included in the LaCosta Island study are the same as those tested at the Dam Neck and Buzzards Bay sites. The systems include organic, organic with cathodic protection, metallic, metal-filled organic, and organic over metal-filled coatings. These were applied after the base metal was sandblasted to near "white metal" according to Steel Structures Painting Council (SSPC) Specification SSPC-SP-10-63T.

The piles were water-jetted into place in three rows parallel to the shoreline (as shown in Figures 4 and 5). The rows were designated A, B, and C, with A being nearest the beach and C farthest. Of the 31 sets of three piles, three were bare carbon or mariner steel, two were prestressed concrete, and the rest were coated steel. One set of coated steel pilings was cathodically protected. The coated piles in row A were completely coated; those in row B also were entirely coated, except for seven 6-in. x 1-in. (152 mm x 25mm)

⁶A. Kumar and D. Wittner, "Coatings and Cathodic Protection of Piling in Seawater: Results of 5-Year Exposure."

Table 1
Test Pile Details, LaCosta Island Test Site

System No.	Type of Piling*	Description of Coating System	No. of Coats	Dry Coating Thickness, mils** (mm)	Coating Source	Remarks
1	H	Bare carbon steel	—	—	—	—
2	H	Bare carbon steel with zinc anodes	—	—	—	2 anodes
3	H	Bare carbon steel with aluminum anodes	—	—	—	2 anodes
4	H	Coal-tar epoxy Formula C-200	2	16-20 (0.41-0.51)	United States Steel (U.S.S.) Chemicals	—
5	H	Coal-tar epoxy with zinc anodes Formula C-200, polyamide-cured	2	16-20 (0.41-0.51)	U.S.S. Chemicals	2 anodes
6	H	Coal-tar epoxy, amine-cured Tarsel	2	16-20 (0.41-0.51)	U.S.S. Chemicals	
7	H	Coal-tar epoxy, aluminum-oxide-armored at Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	(Third coat + garnet to be applied between 11 and 17 ft (3.3 and 5.2 m) from bottom of pile
		Formula C-200 + aluminum oxide (No. 30 grit) broadcast into wet final coat	1	10-11 (0.25-0.28)		
8	H	Aluminum-pigmented epoxy-tar Carbomastic #3	1	8-9 (0.20-0.23)	Carboline Co.	—
		Carbomastic #12-14	1	7-8 (0.18-0.20)		
		Carbomastic #5-140	1	4 (0.10)		
9	H	Coal-tar epoxy			U.S.S. Chemicals	
		U.S.S. epoxy primer	1	3 (0.08)		
		Tarsel Standard	1	8-10 (0.20-0.25)		
		Tarsel Standard	1	8-10 (0.20-0.25)		
10	H	Epoxy over inorganic ceramic Plas-Chem Zinc-ite G primer	1	3-4 (0.8-0.10)	Plas-Chem Corp.	
		Plas-Chem's Ceram-ite #101	1	5-6 (0.13-0.15)		
		Plas-Chem's 2140 Z high-build epoxy	1	7-8 (0.18-0.20)		

*Steel H-piles are 30-ft (9.1 m) lengths of 6 in. x 6 in. (152 mm x 152 mm) wide flange (25 lb/ft [37.2 kg/ml] mild carbon steel. Systems 23, 24, and 25 are mariner steel H piles. Systems 26, 27, and 28 are pipe piles, mild carbon steel, 6 in. (152 mm) diameter, schedule 40, 0.280 in. (0.7 mm) wall thickness. Prestressed concrete piles are stated in this column.

**Film thickness tolerance per coat may be plus or minus 15 percent of given thickness per coat, except where a range is given.

General Notes

All surfaces were blast-cleaned to near-white metal before coating. Systems 28 and 29 were supplied in the near-white condition. Specimens were numbered A, B, or C, which corresponded to their position (A faced the shore, B in the center, and C faced the Gulf of Mexico), and had a numeric prefix which designated the way they were coated.

Table 1 (Cont'd)

System No.	Type of Piling	Description of Coating System	No. of Coats	Dry Coating Thickness, mils (mm)	Coating Source	Remarks	
11	H	Epoxy over inorganic zinc primer Zincor #11 primer	1	1-1.5 (0.03-0.04)	Plas-Chem Corp.		
		Chem-Pon 2310X Red	1	8-9 (0.20-0.23)			
12	H	Saran Washcoat primer, MIL-P-15328B (Formula 117)	1	0.4 (0.01)	Navy stock	Alternate coat white and orange	
		Formula 113/54; MIL-L-18389	7	6-7 (0.15-0.18)			
13	H	Aluminum, flame-sprayed (wire)	1	6 (0.15)	Metalweld, Metco, or other	Steel wire flash bonding coat, 1 mil (0.03 mm)	
14	H	Aluminum, flame-sprayed (wire) vinyl topcoat			Metalweld, Metco, or other	Steel wire bonding 1 mil (0.03 mm)	
		Flame-sprayed aluminum (wire)	1	6 (0.15)			
		Washcoat primer, Formula 117, MIL-P-15328B	1	0.4 (0.01)	Metco, Inc.		
		Alum, vinyl, Metcoscal-A V (Alum, Vinyl)	2	2 (0.05)			
15	H	Zinc, flame-sprayed, with saran topcoat	1	1 (0.03)	Metco, Metal- weld, or other		
		Steel wire flash bond coat	1	6 (0.15)			
		Flame-sprayed zinc (wire)	1	6 (0.15)	Navy stock		
Saran, Formula 113/54, alternate white and orange; finish coat, white	7	6-7 (0.15-0.18)					
16	H	Zinc, flame-sprayed, with Navy vinyl topcoat, flame-sprayed zinc (wire)	1	6 (0.15)	Metco, Metal- weld, or other Navy stock	Steel wire flash bonding coat, 1 mil (0.03 mm)	
		Washcoat primer, MIL-P-15328B	1	0.4 (0.01)			
		Vinyl red-lead, Formula 119, MIL-P-15929	5	4-5 (0.10-0.13)			
17	H	Phenolic Mastic Phenoline 300 (orange)	1	8 (0.20)	Carboline Co.		
		Phenoline 300 (gray) finish coat	1	8 (0.20)			
18	H	Vinyl over inorganic zinc-rich U.S.S. zinc-rich No. 220	1	3 (0.08)	U.S.S. Chemicals		
		U.S.S. high-build vinyl	1	7 (0.18)			
19	H	Coal-tar epoxy over organic zinc-rich U.S.S. zinc-rich epoxy No. 110	1	3 (0.08)	U.S.S. Chemicals		
		Coal-tar epoxy, C-200	2	12 (0.30)			

Table 1 (Cont'd)

System No.	Type of Piling	Description of Coating System	No. of Coats	Dry Coating Thickness, mils (mm)	Coating Source	Remarks
20	H	Epoxy-polyamide over inorganic zinc-rich Carbozine #11	1	3 (0.08)	Carboline Co.	
		High-build epoxy polyamide 190 HB	2	12 (0.30)		
21	H	Epoxy-tar over inorganic zinc-rich Carbozine #11	1	3 (0.08)	Carboline Co.	
		Carbomastic #14	1	8 (0.20)		
22	H	Vinyl mastic over inorganic zinc-rich Dimetacote #3+D3 Curing Solution	1	3 (0.08)	Amercoat Corp.	Curing solution to be removed by freshwater wash
		#54 Tie Coat	1	1 (0.03)		
		Vinylmastic #87	1	10 (0.25)		
23	H	Bare mariner steel	—	—	—	—
24	H	Bare mariner steel with zinc anodes	—	—	—	2 anodes
25	H	Coal-tar epoxy on mariner steel Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	
26	Pipe	Bare carbon steel	—	—	—	—
27	Pipe	Coal-tar epoxy Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	
28	Pipe	Coal-tar epoxy, garnet-armored at mud line Formula C-200	2	16-20 (0.41-0.51)	U.S.S. Chemicals	Third coat and aluminum oxide to be applied between 11 and 17 ft (3.3 and 5.2 m) from bottom of pile
		Formula C-200 + aluminum oxide (#30 grit) broadcast into wet final coat	1	10 (0.25)		
29	H	Polyester glassflake, Carboglas 1601, spray grade	2	40 (1.02)	Carboline Co.	Blast material to provide 3 to 4 mil (0.08 to 0.10 mm) surface profile
30		Prestressed concrete 10 in. (254 mm) square				
31		Prestressed concrete 10 in. (254 mm) octagon				

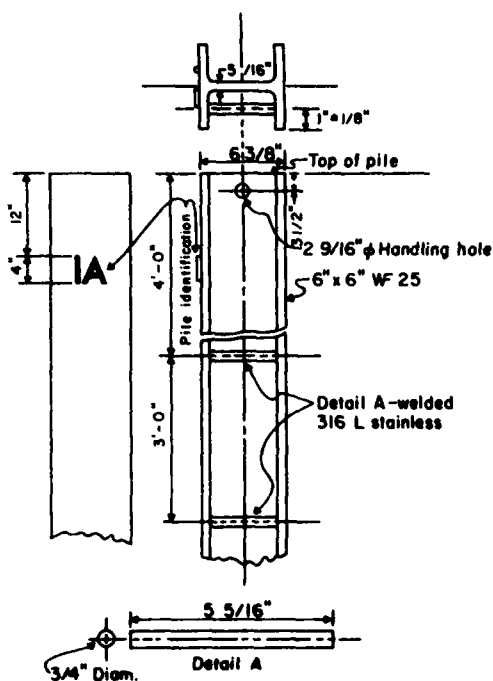


Figure 2. Dimensions of H piles (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

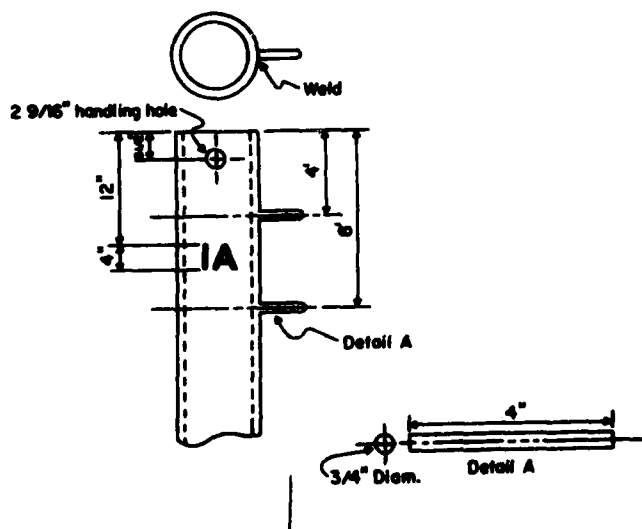


Figure 3. Dimensions of pipe piles (metric conversion factor: 1 in. = 25.4 mm).

windows at 2, 7, 14, 17, 20, 22, and 27 ft (0.6, 2.1, 4.3, 5.2, 6.1, 6.7, and 8.2 m) from the bottom of the pile on the surface facing the beach. The C piles, removed in 1976 after 5-years' exposure, were completely coated except for the embedded zone.*

The sacrificial anodes for the cathodically protected piling were mounted near the sand-swept zone. The zinc anodes were 4 in. x 4 in. x 36 in. (101 mm x 101 mm x 914 mm) and weighed about 150 lb (68.0 kg) when new; and aluminum anodes were 4 in. x 4 in. x 38 in. (101 mm x 101 mm x 967 mm) and weighed 60 lb (27.2 kg) when new. Two zinc or aluminum anodes were installed on each pile to be cathodically protected.

Annual Inspection

After placement in 1971, the piling had five annual inspections consisting of visual observations and electrochemical measurements. From 1977 to 1980, coating performance was inspected only visually. In 1981, CERL performed electrochemical measurements and a visual inspection, including a complete evaluation of coating deterioration in accordance with ASTM Standard Methods for Evaluating Degree of Rusting on Painted Steel Surfaces (Table 2).

Three types of electrical measurements were taken: pile corrosion potential, cathodic protection index (CPI), and polarization. Electrical contact with the stainless steel rods on the pilings was made with vise clamps connected to the cable wires. The protection offered by sacrificial anodes was assessed by pile potential measurements. A Miller Model M-3D Multi-meter, or the equivalent, was used to measure the potential with respect to a copper-copper sulphate reference immersed in seawater.

The CPI of a coated piling was determined by forming a galvanic couple between it and a bare pile, and measuring the potential of the coated pile with zero applied current. The current was then increased to lower the initial potential to -0.85 volts (V) for the coated pile. The current was constantly adjusted to keep the coated pile at -0.85 V during a 5-minute period. The initial and final values of the current and

*For this study, each 30-ft (9.1-m) length of piling can be divided into four zones: the atmospheric zone (0 to 6 ft, or 0 to 1.8 m), the immersed zone (6 ft to 17 ft, or 1.8 m to 5.2 m), the sand-swept zone (17 ft to 21 ft, or 5.2 m to 6.4 m), and the embedded zone (21 ft to 30 ft, or 6.4 m to 9.1 m).

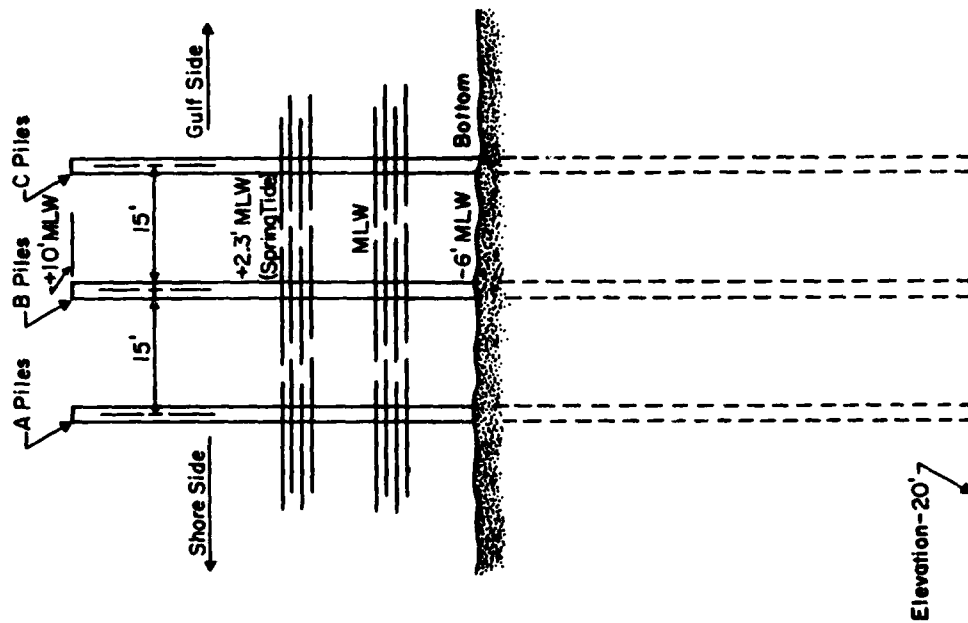


Figure 5. Elevation of pile set for LaCosta Island test site (metric conversion factor: 1 ft = 0.3048 m).

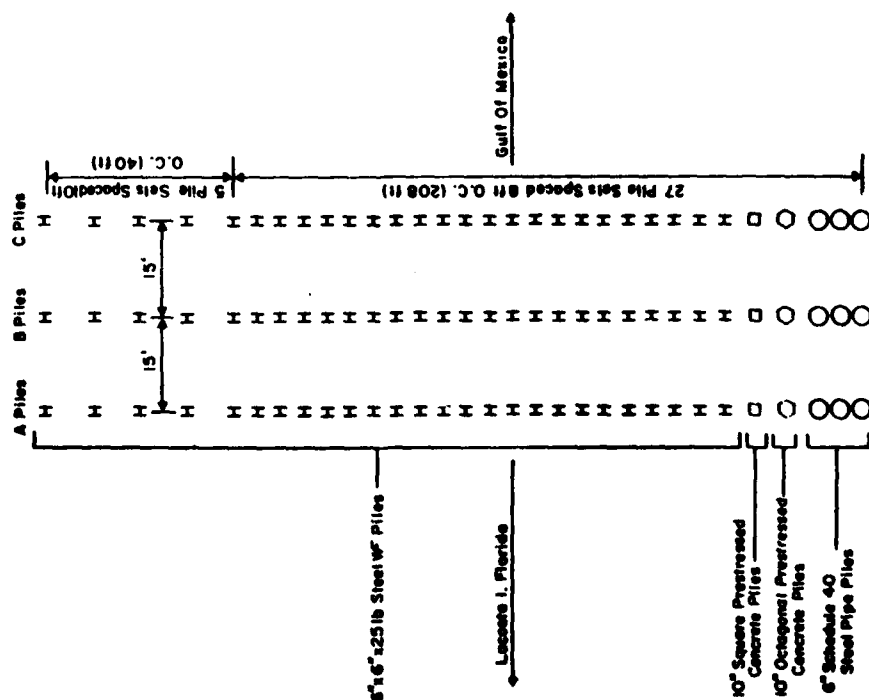


Figure 4. Plan of LaCosta Island test piles (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

potential were then used to calculate the CPI value with Eq 1:

$$CPI = \Delta V / \Delta I \quad [\text{Eq 1}]$$

where ΔV = change in voltage

ΔI = current required to shift the voltage.

The corrosion rate measurements were conducted by Schwerdtfeger and McDorman's "polarization break" method, which uses breaks in the anodic and cathodic polarization curves to identify the corrosion rate by a calculated corrosion current, I_c .⁷ I_c can be calculated from the following relationship, which was derived by Pearson and confirmed by Holler.⁸

$$I_c = \frac{(I_p)(I_q)}{(I_p + I_q)} \quad [\text{Eq 2}]$$

where I_p and I_q equal the tangent intersection of the portions of the anodic and cathodic curves, respectively. These curves were obtained by increasing the current from zero in small increments at 3-minute intervals. After each time period, both the current and the test pile potential (with respect to copper-copper sulphate reference cell) were noted.

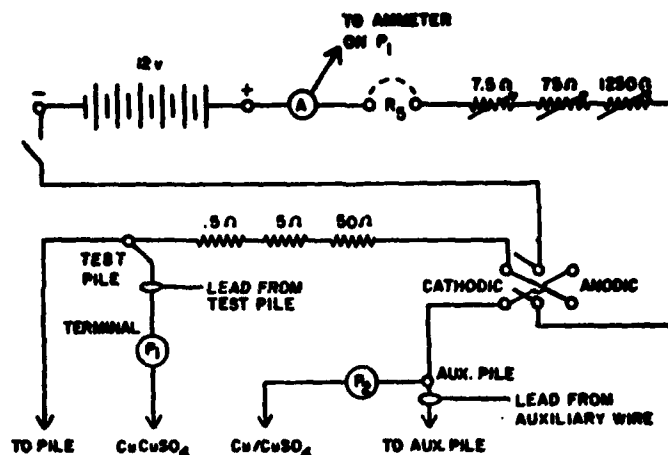
Figure 6 is the circuit diagram of the instrument used for the polarization and CPI measurements.

Ten-Year Inspection

Most piles in rows A and B were removed in March 1981 after 10-years' exposure. All piles were removed by hooking a crane onto the pull-holes provided. Water jetting was used to loosen the bottom material around the piling to prevent damage to the coating systems. After removal, the piles were transported by barge to a storage area where they were unloaded onto wood supports and spaced to allow easy access and room to turn the piling for inspection of all surfaces. The piles were cleaned of guano and marine organisms by

⁷W. J. Schwerdtfeger and O. N. McDorman, "Measurement of Corrosion Rate of Metal From Its Polarizing Characteristics," *Journal of the Electrochemical Society*, Vol 99 (1952), p 407.

⁸J. M. Pearson, "Null Methods Applied to Corrosion Measurements," *Transactions of the Electrochemical Society*, Vol 81 (1942), p 485; H. D. Holler, "Studies on Galvanic Couples," *Journal of the Electrochemical Society*, Vol 97 (1950), p 277.



P_1 = MILLER M-3 PM/VM OR HIGH RESISTANCE VM; USED FOR MONITORING POTENTIAL/VOLTAGE OF TEST PILES.

P_2 = MILLER M-3; FOR AUXILIARY PILE VOLTAGE

Figure 6. Circuit diagram for measurement of cathodic protection index and polarization measurements.

hand-scraping and water wash when necessary. Charts were drawn to display the corrosion behavior of the piling (see the appendix), and the coated piles were rated in accordance with ASTM D 610-68 (Tab⁹: 2).

The bare steel piles and the coated steel piles with cathodic protection had to be sandblasted before their flange thicknesses could be measured along the length of each pile and a profile made.

3 RESULTS AND DISCUSSION

Visual Observations of Protective Coating Systems

Table 3 presents the ASTM D 610-68 visual evaluation results for the coated steel piling after the 5- and 10-year exposures. Charts of coating degradation after 10-years' exposure are shown in the appendix; a brief description of the coating systems' performance is presented below. (The degradation noted in the piling's atmospheric zone was caused by salt spray.)

1. System 4 was a C-200 coal-tar epoxy coating. This system showed some rusting in the atmospheric zone. Rusting and pitting with loss of coating, especially at the flange, was present in the immersed zone edge. In the immersed zone, there was attached marine growth.

Table 2
Scale and Description of Rust Grades*

Rust Grades**	Description	SSPC-ASTM Photographic Standard
10	No rusting or less than 0.01 percent of surface rusted	unnecessary
9	Minute rusting, less than 0.03 percent of surface rusted	No. 9
8***	Few isolated rust spots, less than 0.01 percent of surface rusted	No. 8
7	Less than 0.3 percent of surface rusted	none
6****	Extensive rust spots but less than 1 percent of surface rusted	No. 6
5	Rusting to the extent of 3 percent of surface rusted	none
4+	Rusting to the extent of 10 percent of surface rusted	No. 4
3++	Approximately one-sixth of the surface rusted	none
2	Approximately one-third of the surface rusted	none
1	Approximately one-half of the surface rusted	none
0+++	Approximately 100 percent of the surface rusted	unnecessary

*Reprinted, with permission, from the Annual Book of ASTM Standards, Part #27. Copyright, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

**Similar to European Scale of Degree of Rusting for Anti-Corrosive Paints (1961) (black and white).

***Corresponds to SSPC Initial Surface Conditions (0 to 0.1 percent) and BISRA (British Iron and Steel Research Association) 0.1 percent.

****Corresponds to SSPC Initial Surface Conditions F (0.1 to 1 percent) and BISRA (1.0 percent).

+Corresponds to SSPC Initial Surface Condition G (1 to 10 percent).

++Rust grades below 4 are of no practical importance in grading performance of paints.

+++Corresponds to SSPC Initial Surface Condition H (50 to 100 percent).

2. System 5 was a C-200 coal-tar epoxy/polyamide-cured coating with zinc anodes. Light rust and scale were present in atmospheric zone, with some loss of the coating in the immersed zone.

3. System 6 was a coal-tar epoxy/amine-cured coating. Severe loss of coating in the immersed zone occurred. Some rust and scale were in the atmospheric zone.

4. System 7 was a C-200 coal-tar epoxy coating with aluminum oxide grit added to the final coat of C-200 coal-tar epoxy along the mudline. Light rust and scale were in the atmospheric zone, with some loss of coating in the immersed zone.

5. System 8 consisted of an aluminum pigmented epoxy-tar applied over two coats of epoxy tar. There was light rusting along the flange edges in the atmospheric zone. The immersed zone was severely rusted and pitted.

6. System 9 was an epoxy primer/coal-tar epoxy. This coating system was in excellent condition in the atmospheric zone. There was some rusting of flange edges in the immersed zone.

7. System 10 was a coating consisting of a zinc-rich primer, a ceramic intermediate coat, and a high-build epoxy topcoat. The coating system showed light staining in both the atmospheric and immersed zones, but overall was in good condition.

8. System 11 consisted of a zinc-rich primer with an epoxy topcoat. The coating in the immersed and atmospheric zones was degraded, causing severe rusting and pitting on the steel piling.

9. System 12 consisted of a washcoat primer with a saran topcoat. This coating system gave fair protection in the atmospheric zone, where light rust and scale were present, but was completely removed in the immersed zone, where the piling showed rusting and pitting.

10. System 13 was a flame-sprayed aluminum coating. Light scale and rusting, present along the length of the piling, was most severe at the splash zone, where there was no sacrificial protection.

11. System 14 consisted of a flame-sprayed aluminum coating with a vinyl topcoat. Staining and rust were present in the atmospheric zone. The coating was

Table 3
Visual Evaluation of Coating Performance After 5- and 10-Years' Exposure

System Class	System Type	System Number	5-Year Exposure* Zones Evaluated		10-Year Exposure** Zones Evaluated	
			Atmospheric	Immersed	Atmospheric	Immersed
Organic	Coal-tar (Tarsol)	9	10	8	10	8
	Coal-tar/armored	7	6	8	6	7
	Coal-tar on mariner	25	9	4	7	3
	Coal-tar (Tarsol)	6	7	3	6	3
	Coal-tar (C-200)	4	9	4	8	3
	Saran	12	10	0	7	0
	Phenolic Mastic	17	7	8	6	4
	Polyester glass flake, Carboglas 1601	29	10	10	10	10
Metal-filled	Aluminum pigmented epoxy-tar	8	9	3	8	3
Organic over metal-filled	Epoxy over Zn-rich	20	9	6	9	6
	Epoxy/cermmite					
	Vinyl/inorganic Zn-rich	10	10	9	8	9
	Coal-tar over Zn-rich	18	10	9	4	6
	Epoxy/inorganic Zn-rich	11	6	1	2	0
	Epoxy tar/inorganic Zn-rich	21	9	1	8	0
	Vinyl mastic/inorganic Zn-rich	22	7	2	9	0
Metallic	Flame-sprayed, AL	13	7	8	3	5
Organic over metallic	Vinyl (Al)	14	8	7	5	7
	Vinyl (Zn)	16	10	8	9	7
	Saran (Zn)	15	5	1	5	1
Organic coating with cathodic protection	Coal-tar epoxy with zinc anodes	5	10	9	8	9

*Row C pilings with seven windows.

**Row A pilings were completely coated.

+Values refer to rust grades in Table 2.

excellent in the immersed and embedded zones, indicating that the flame-sprayed aluminum was still providing sacrificial protection.

12. System 15 was a flame-sprayed zinc coating with a saran topcoat. Staining and light rust were present in the atmospheric zone. The saran topcoat was completely gone from the immersed zone, but the flame-sprayed zinc still provided protection.

13. System 16 consisted of a flame-sprayed zinc coating with a vinyl topcoat. Rust was present in the splash zone. The vinyl topcoat had peeled off in the immersed zone, and there was some light staining.

14. System 17 was a phenolic mastic coating. Light rust and staining were present in the atmospheric zone. Pitting on steel flange edges and severe loss of coating had occurred in the immersed zone.

15. System 18 consisted of an inorganic zinc-rich primer with a high-build vinyl topcoat. Scale and rust were present in the atmospheric zone, and some light rust and staining had occurred in the immersed zone.

16. System 19 was a coal-tar epoxy with organic zinc-rich primer. Some rust and blistering were present in the atmospheric zone. In the immersed zone, there was severe loss of coating, with rusting and pitting.

17. System 20 consisted of an inorganic zinc-rich primer with a high-build epoxy-polyamide. Light rust and scale were present in the tidal zone. Overall, the coating's condition was very good.

18. System 21 was an epoxy-tar over an inorganic zinc-rich primer. Some light rust was present along the flange edge in the atmospheric zone. There was complete loss of coating in the immersed zone, with severe rusting and pitting. The coating had blistered in the embedded zone.

19. System 22 was a vinyl mastic topcoat over an inorganic zinc-rich primer. Light staining was present in atmospheric zone; complete loss of coating occurred in the immersed zone; dense blistering and rusting were present in the embedded zone.

20. Coating system 25 was a C-200 coal-tar epoxy on mariner steel (ASTM 619). This coating exhibited the same characteristics as system 4, which was C-200 on carbon steel A36.

21. System 29 was a polyester glass flake 40-mils (1.02 mm) thick. No rust stains were observed in the tidal and atmospheric zones. The pile was left intact.

Categories of Coatings

For discussion, the protective coating systems used in this study can be divided into six categories: organic, organic with cathodic protection, metal-filled, organic over metal-filled, metallic, and organic over metallic. The condition of these coating systems after 10-years' exposure is outlined below.

Organic Coatings (Systems 4, 6, 7, 9, 12, 17, 27 and 29)

In this class of coatings, the polyester glass flake (System 29) made by Carboline Co. was the top performer. According to Carboline, this coating resists "severe chemicals including hypochlorites and free chlorine. . . . A 40 mil film contains. . . about 160 layers of Flakeglas making the film very resistant to penetration in many aggressive environments. Tight adhesion is maintained even after long aging. The coating. . . [resists] abrasion and impact. The standard system is two 20 mil coats, spray applied. No primer is required. Carboglas 1601 SG can be readily applied by conventional spray. Rolling or brushing after application is not required."⁹

Coal-tar epoxy over epoxy primer (System 9) provided good protection, as did the coal-tar epoxy with aluminum oxide armor (System 7) and coal-tar epoxy over mariner steel (System 25). The phenolic mastic (System 17) offered fair protection, while C-200 coal-tar epoxy (System 4), Tarsel coal-tar (System 6), and saran (System 12) provided poor protection. Most of the damage to the organic coatings in the immersed zone seemed to be caused by barnacles and other marine organisms.

Organic With Cathodic Protection (System 5)

System 5 was a coal-tar epoxy coating with zinc anodes. The organic coal-tar epoxy coating provided adequate protection to the exposed pile in the atmospheric zone. The immersed zone suffered severe loss of the organic coating, but the steel pile was in excellent condition because of the cathodic protection provided by the sacrificial zinc anodes.

⁹ "Carboglas 1601 Spray Grade (SG)," Product Data Sheet (Saint Louis, MO: Carboline Co.).

Metal-Filled (System 8)

The one system in the metal-filled class—aluminum pigmented epoxy-tar—performed poorly in the immersed and sand-swept zones. This was a three-coat system in which two coats of epoxy-tar electrically insulated, thus preventing the outer coat containing the aluminum pigment from sacrificially protecting the steel pile. The coating was perforated by barnacles, which caused severe pitting in the immersed zone.

Organic Over Metal-Filled (Systems 10, 11, 18, 19, 20, 21 and 22)

The effectiveness of this coating class usually depends on the metal-filled primers' providing sacrificial protection to any exposed steel in the immersed zone of the piling. After 10 years of exposure, Systems 20, 10, and 18 were rated excellent; potential measurements indicate that the zinc-rich primers of these systems were still providing sacrificial protection. Systems 19, 11, 21 and 22 were all rated poor in the immersed and sand-swept zones after 10-years' exposure. Potential measurements indicated that the sacrificial metal-filled primers were gone; therefore, the bare steel was no longer being protected.

Metallic (System 13)

The flame-sprayed aluminum coating of System 13 provided fair protection in the atmospheric zone, where sacrificial aluminum is not advantageous. The protection provided by this coating was rated good in the immersed and sand-swept zones.

Organic Over Metallic (Systems 14, 15 and 16)

Overall, this classification was rated very good. In the vinyl system, the aluminum flame-sprayed undercoat (System 14) provided better protection in the immersed and sand-swept zones than the zinc flame-sprayed undercoat (System 16). Saran over zinc flame-sprayed undercoat also provided very good protection in the immersed and the sand-swept zones. Vinyl over flame-sprayed zinc provided excellent protection in the atmospheric zone. Potential measurements indicated that the flame-sprayed metals in Systems 14 and 15 still offered sacrificial protection after 10-years' exposure.

Electrochemical Measurements

Potential Measurements

The potentials of the cathodically protected piles were measured with respect to a copper-copper sulfate reference cell (Table 4). The results of the 1972, 1976, and 1981 inspections showed that no significant changes in potentials have occurred, and that the sacrificial anodes were providing protection in the immersed zone.

CPI Measurements

The CPI indicates the current required to cathodically protect a pile's bare area in the immersed zone. The index reflects the amount of current required to shift the potential of the pile in the cathodic direction to attain -0.85 V with respect to a copper-copper sulphate reference cell. Table 5 shows the CPI for the coated piling at the LaCosta Island test site.

Table 4
Potential Measurements: Piling With Sacrificial Anode Cathodic Protection

System Type	System Number	Voltage, 1972	Voltage, 1976	Voltage, 1981	Anode Consumption (lb/yr)
Bare carbon steel (A36) with zinc anodes	2A	1.080	1.11	1.094	2.1
	2B	1.080	1.05	1.080	1.8
	2C	1.080	1.10	—	—
Bare carbon steel (A36) with aluminum anodes	3A	0.990	1.09	1.043	1.7
	3B	0.990	1.05	1.035	1.5
	3C	0.995	1.05	—	—
C-200 coal-tar epoxy on A36 with zinc anodes	5A	1.080	1.09	1.105	<0.1
	5B	1.100	1.10	1.108	<0.1
	5C	1.090	1.09	—	—
Bare mariner steel (690) with zinc anodes	24A	1.075	1.10	1.091	2.72
	24B	1.080	1.10	1.090	2.2
	24C	1.080	1.10	—	—

Table 5
Cathodic Protection Indices of Coated Piling

Pile Number and Row	$\frac{\Delta V}{\Delta A}$					
	1972	1973	1974	1975	1976	1981
4A	8.95	3.61	1.6	1.14	1.72	0.41
4B	2.38	1.72	1.1	0.71	1.63	0.29
6A	7.00	2.21	1.3	0.76	1.54	0.50
6B	1.45	0.930	0.68	0.59	1.89	0.34
7A	13.0	9.10	7.2	5.67	5.06	2.23
7B	3.02	2.46	2.0	1.98	2.43	1.17
8A	21.7	3.76	1.7	0.92	1.72	0.60
8B	2.48	1.48	1.1	0.59	4.59	0.28
9A	19.7	15.5	11.0	8.42	7.23	2.80
9B	1.97	1.94	1.6	1.46	2.11	0.87
11A	0.30	0.14	0.12	0.11	1.37	0.19
11B	0.26	0.14	0.11	0.11	1.30	0.29
12A	0.27	0.16	0.12	0.11	1.40	0.18
12B	0.51	0.23	0.15	0.13	1.36	0.26
13A	3.85	5.17	5.4	4.69	4.59	0.57
13B	3.66	5.12	5.7	6.00	5.00	1.39
14A	6.45	3.23	0.2	13.64	16.30	6.00
14B	4.20	5.36	5.6	7.50	5.25	2.03
15A	0.52	0.79	0.81	1.13	2.34	2.00
15B	0.43	0.59	0.75	1.07	2.54	0.26
16A	0.73	0.89	1.5	2.11	3.49	2.05
16B	0.99	0.94	0.13	1.97	4.69	0.0
17A	11.3	4.11	2.9	1.47	2.04	0.58
17B	2.27	1.88	1.3	1.03	1.74	0.48
18A	34.2	17.4	10.0	6.30	0.46	1.38
18B	2.47	2.2	1.6	1.30	1.91	0.64
19A	2.18	0.33	0.21	0.19	1.50	0.22
19B	0.98	0.28	0.17	0.16	1.32	0.17
20A	70.80	46.90	21.0	23.08	16.85	0.0
20B	2.63	2.73	3.7	4.05	5.67	0.98
21A	53.6	39.0	24.0	48.39	16.00	0.22
21B	2.05	1.41	0.65	0.35	1.35	0.18
22A	1.98	2.13	0.32	0.18	1.34	0.14
22B	2.79	2.03	0.50	0.27	1.33	0.17
25A	15.4	5.00	1.7	1.07	18.91	0.39
25B	2.52	1.53	0.78	0.62	1.74	0.32
29A	17.9	12.50	10.0	7.92	7.69	5.80
29B	2.44	2.38	2.0	2.14	2.88	1.92

A direct correlation exists between bare steel area and the amount of current required to shift the bare steel to a fixed potential. Since CPI is inversely proportional to the change in current (Eq 1), a direct correlation exists between the CPI and a bare steel surface in water. A decrease in CPI indicates a larger area of bare steel exposed to water, and is therefore a measure of coating deterioration.

Plotting the cathodic protection indices versus time on log-log plots (Figure 7) permits predictions of the deterioration of the coatings over a long period of time. Deterioration of the coatings generally causes a drop in CPI, as demonstrated by a negative slope. However, some coatings, such as flame-sprayed metallics, have a completely flat slope or a slightly positive one, indicating formation of protective corrosion products, such as aluminum oxide or zinc oxide.

Polarization Measurements

The corrosion rate or rate of metal loss is a function of the average corrosion current density. The higher the corrosion current density of a metal in water, the higher the metal loss. The corrosion current densities—based on Schwerdtfeger's equation (Eq 2)—for bare carbon steel (System 1) and bare mariner steel (System 23) were 14.2 and 16.2 mA/sq ft (152.7 and 174.2 mA/m²), respectively. The corrosion rates as measured by Schwerdtfeger's equation for bare carbon steel (A36) and bare mariner steel (A690) were 7.1 and 8 mils (0.18 and 0.2 mm) per year, respectively. I_p and I_q were determined by extending the tangents of linear portions of the polarization curves and determining their intersection, as shown in Figures 8 and 9.

Flange Thickness Profiles

Figures 10 through 15 give flange edge thickness profiles for piles that were bare, bare with cathodic protection, and coated with sacrificial anodes. The flange thickness was measured 1 in. (254 mm) from the edge, and reflected the corrosion on both surfaces of the piling flange. The corrosion rates determined from these measurements are 7 and 6 mils (0.179 and 0.15 mm) per year respectively for bare carbon (A36) and bare mariner (A690) steel.

All piling of bare carbon and mariner steel showed perforation of the web in the atmospheric zone. No significant differences in corrosion rates were noted between the bare carbon and mariner steel after 10-years' exposure at the LaCosta Island test site. The bare steel piles were severely corroded directly above the high tide (splash) zone and just below the low tide area. A zone of severe corrosion also was found at or just below the piling's mud line. The bare steel piling exhibited very little corrosion in the embedded zone.

Using sacrificial zinc or aluminum anodes on bare steel piling (Figures 12, 13, and 14) effectively reduced the corrosion rate in the immersed and embedded

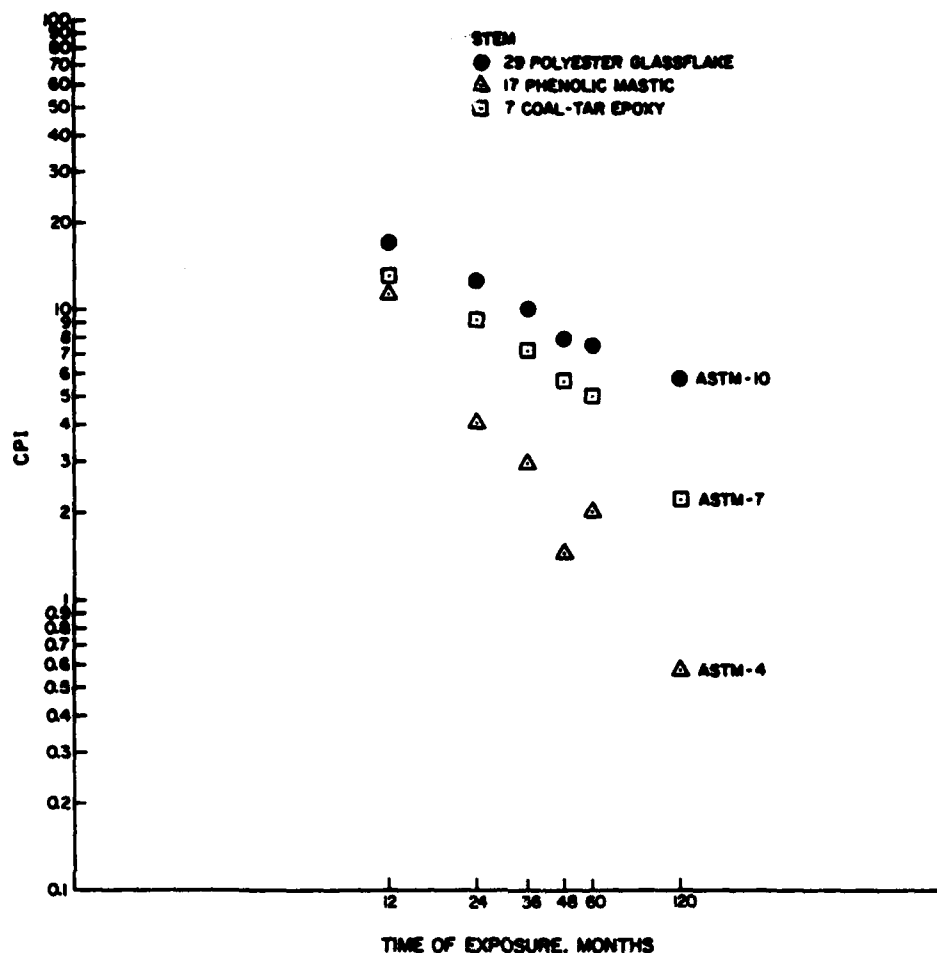


Figure 7. Cathodic protection indices versus time.

zones to less than 0.1 mil (0.003 mm) per year, but had no effect on corrosion in the atmospheric and splash zones.

Adding a coating (Figure 15) to a cathodically protected system reduced the corrosion in the atmospheric zone; anode consumption rates were also reduced. A coated, cathodically protected system is advantageous because the steel is protected when the coating in the immersed zone is damaged.

4 CONCLUSIONS

1. The corrosion rates—determined by flange thickness measurements in the immersion zone—were 7

and 6 mils (0.179 and 0.15 mm) per year respectively for bare carbon (A36) and bare mariner (690) steel. Sacrificial zinc or aluminum anodes effectively reduced corrosion in the immersed zone to less than 0.1 mil (0.003 mm) per year. (Adding sacrificial anodes to a coated steel piling protects steel in the immersed zone if the coating is damaged.)

2. The polyester glass flake coating (System 29) was the top performer. Epoxies over zinc-rich primers (Systems 20, 10 and 18) and vinyl-sealed, flame-sprayed aluminum and zinc (Systems 14 and 16) coatings also performed very well after 10-years' exposure at the LaCosta Island test site. The results are summarized in Table 3.

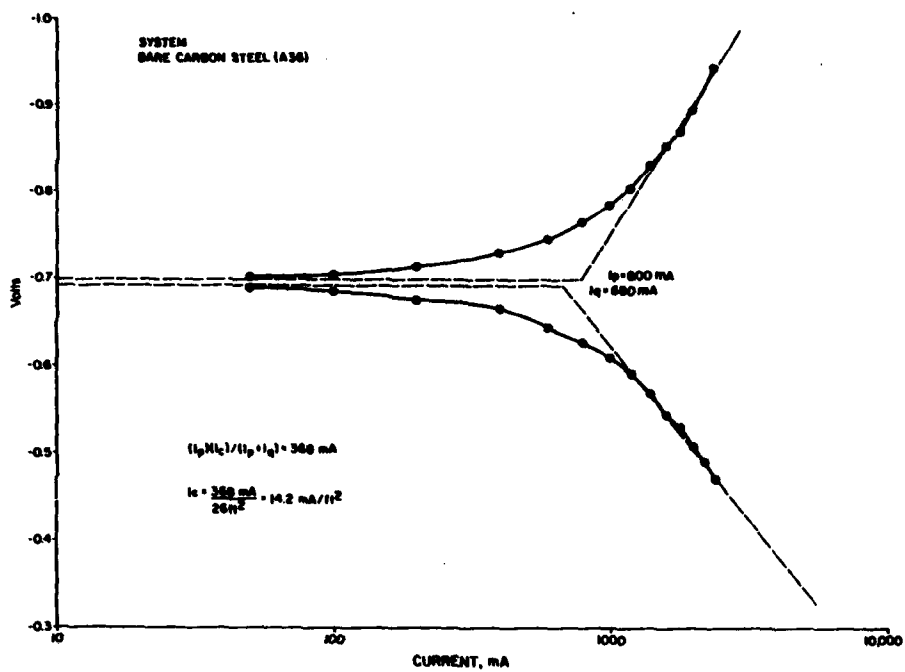


Figure 8. Polarization curves—bare carbon steel.

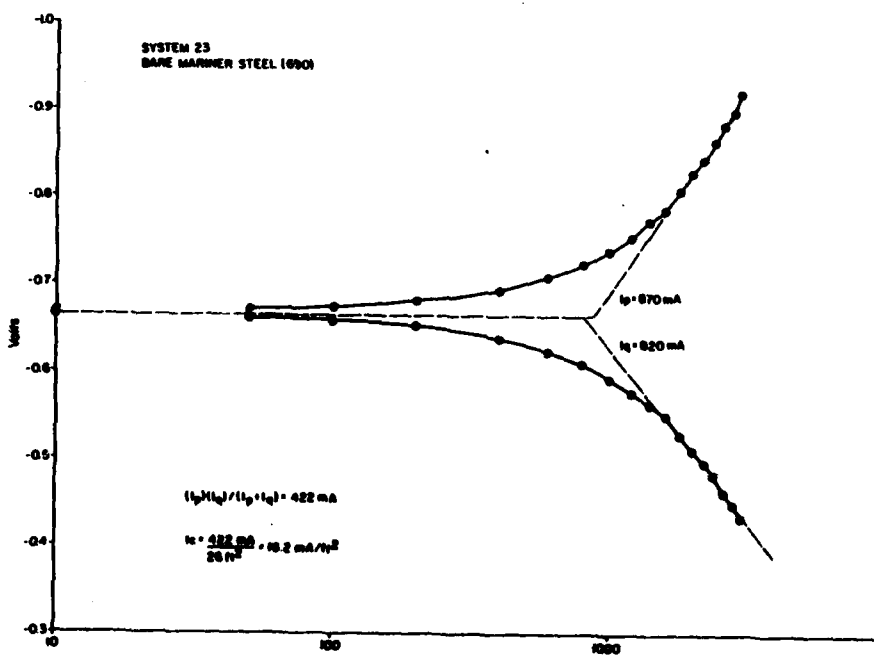


Figure 9. Polarization curves—bare mariner steel.

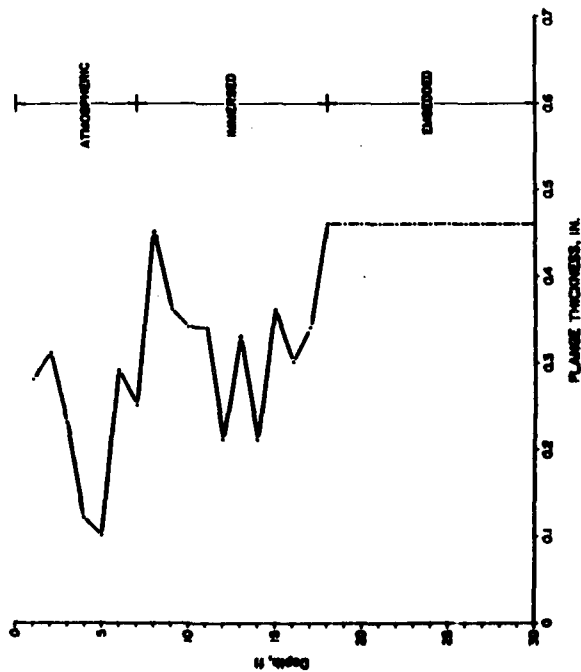


Figure 10. Flange thickness for pile 1B, bare carbon steel (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

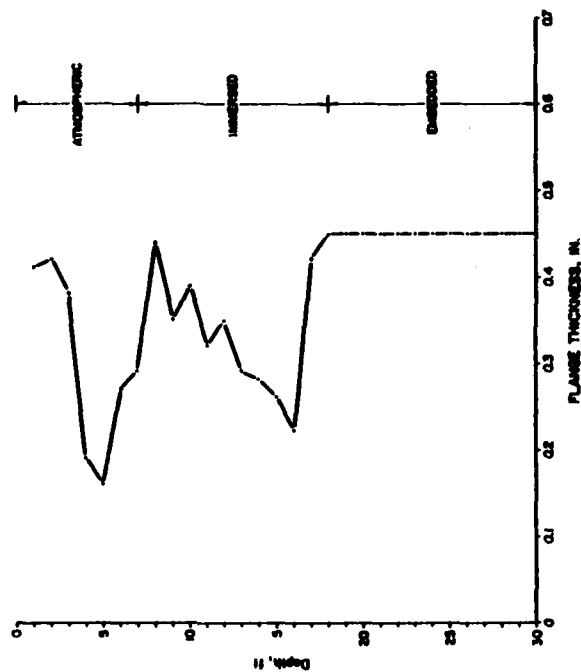


Figure 11. Flange thickness for pile 23B, bare mariner steel (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

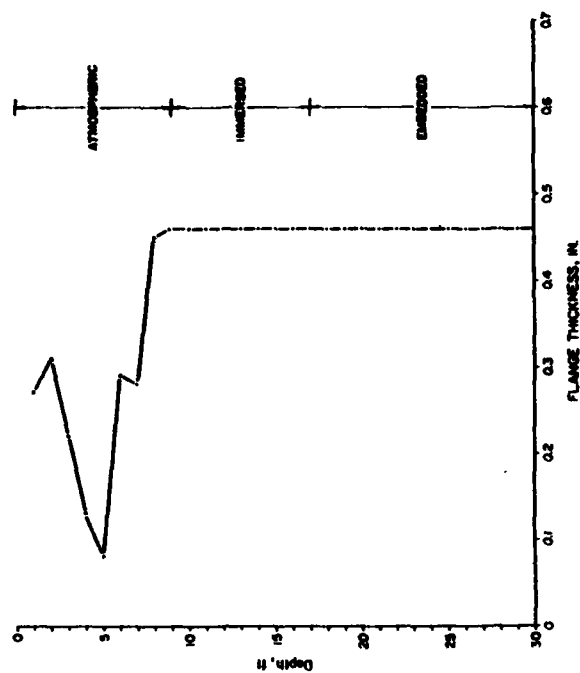


Figure 13. Flange thickness for pile 3B, bare carbon steel with aluminum anodes (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

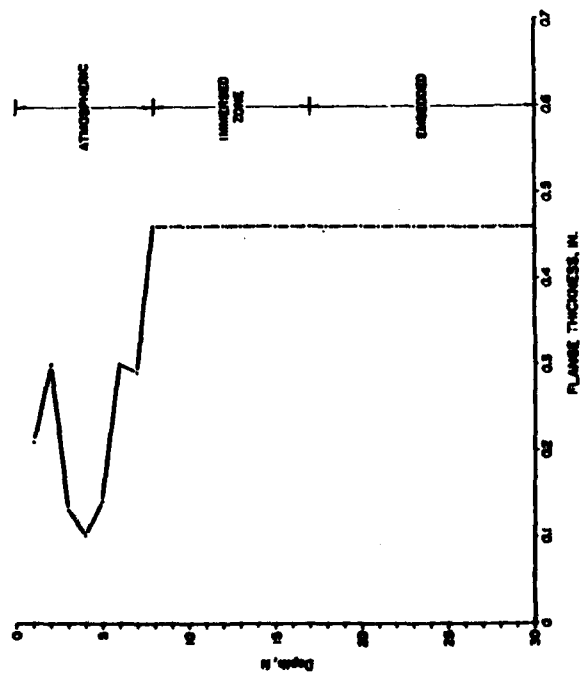


Figure 12. Flange thickness for pile 2B, bare carbon steel with zinc anodes (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

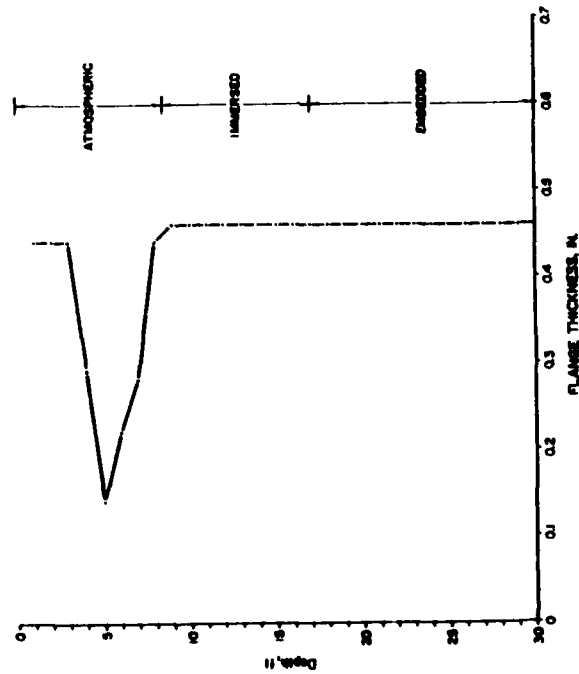


Figure 14. Flange thickness for pile 24B, bare mariner steel with zinc anodes (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

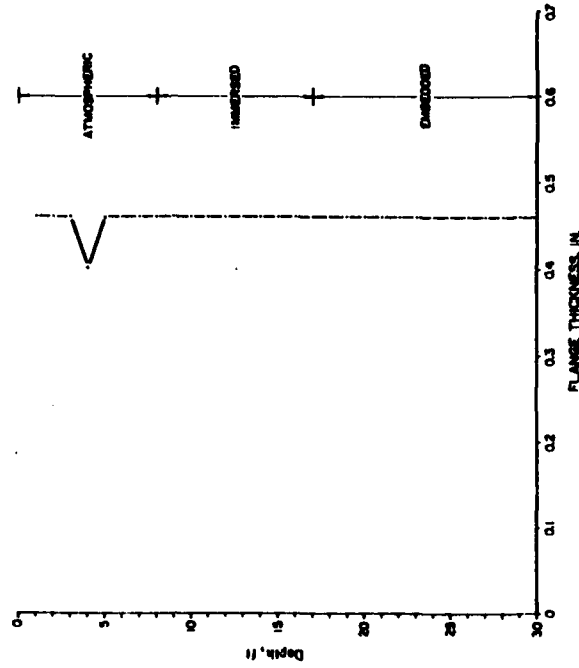
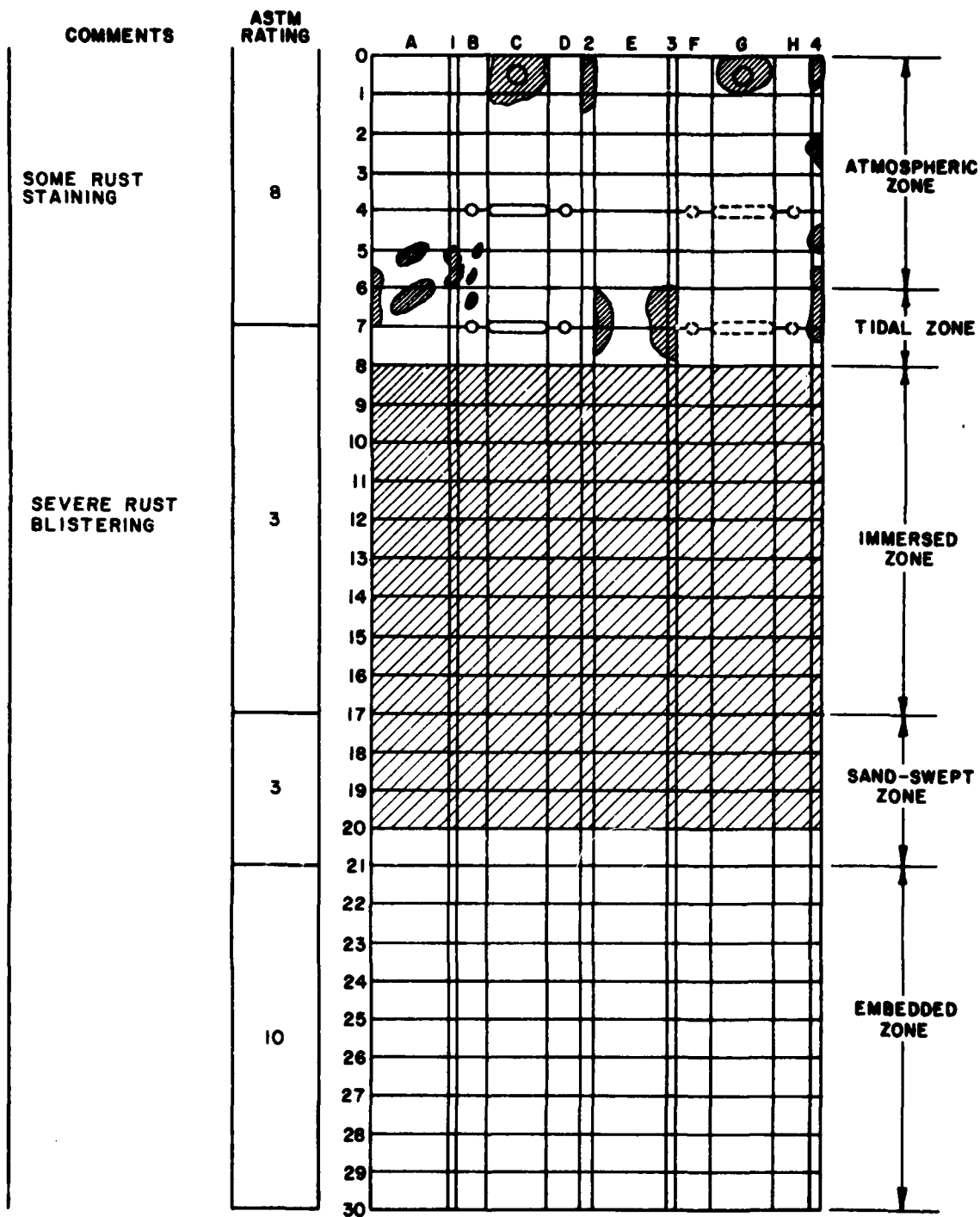


Figure 15. Flange thickness for pile 5B, coal-tar epoxy with zinc anodes (metric conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m).

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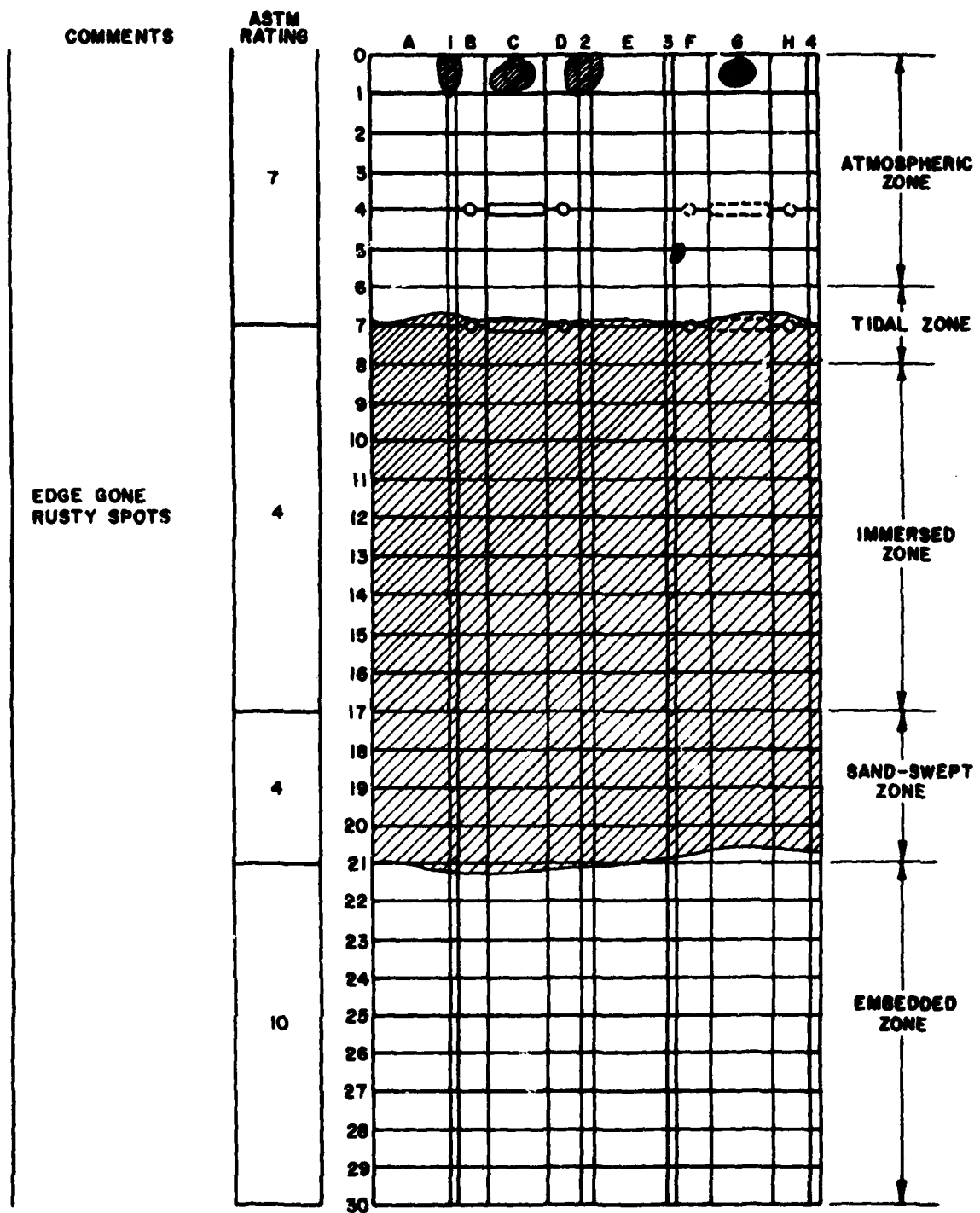
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**APPENDIX:
CHARTS OF CORROSION BEHAVIOR
OF STEEL PILING AT
LACOSTA ISLAND**



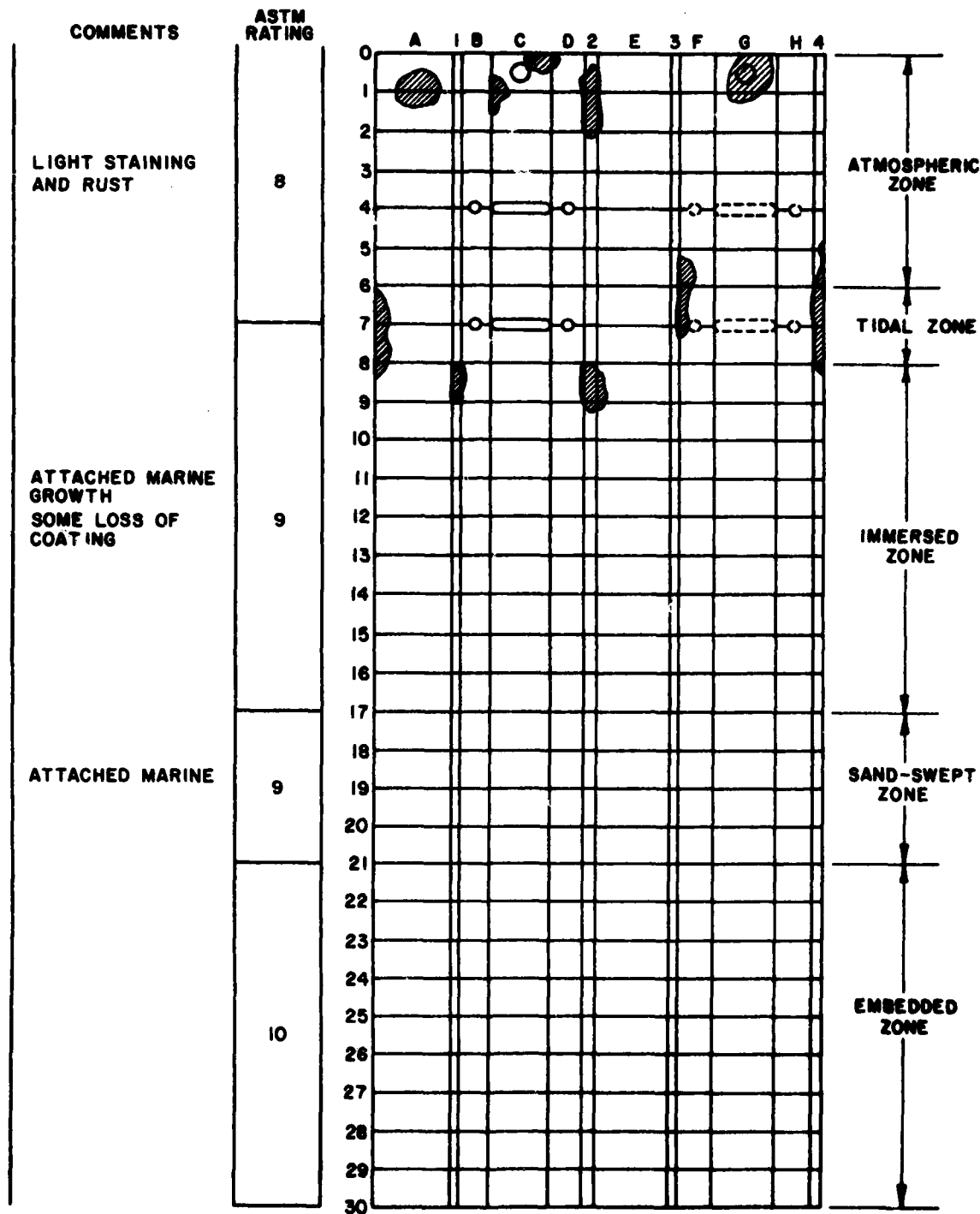
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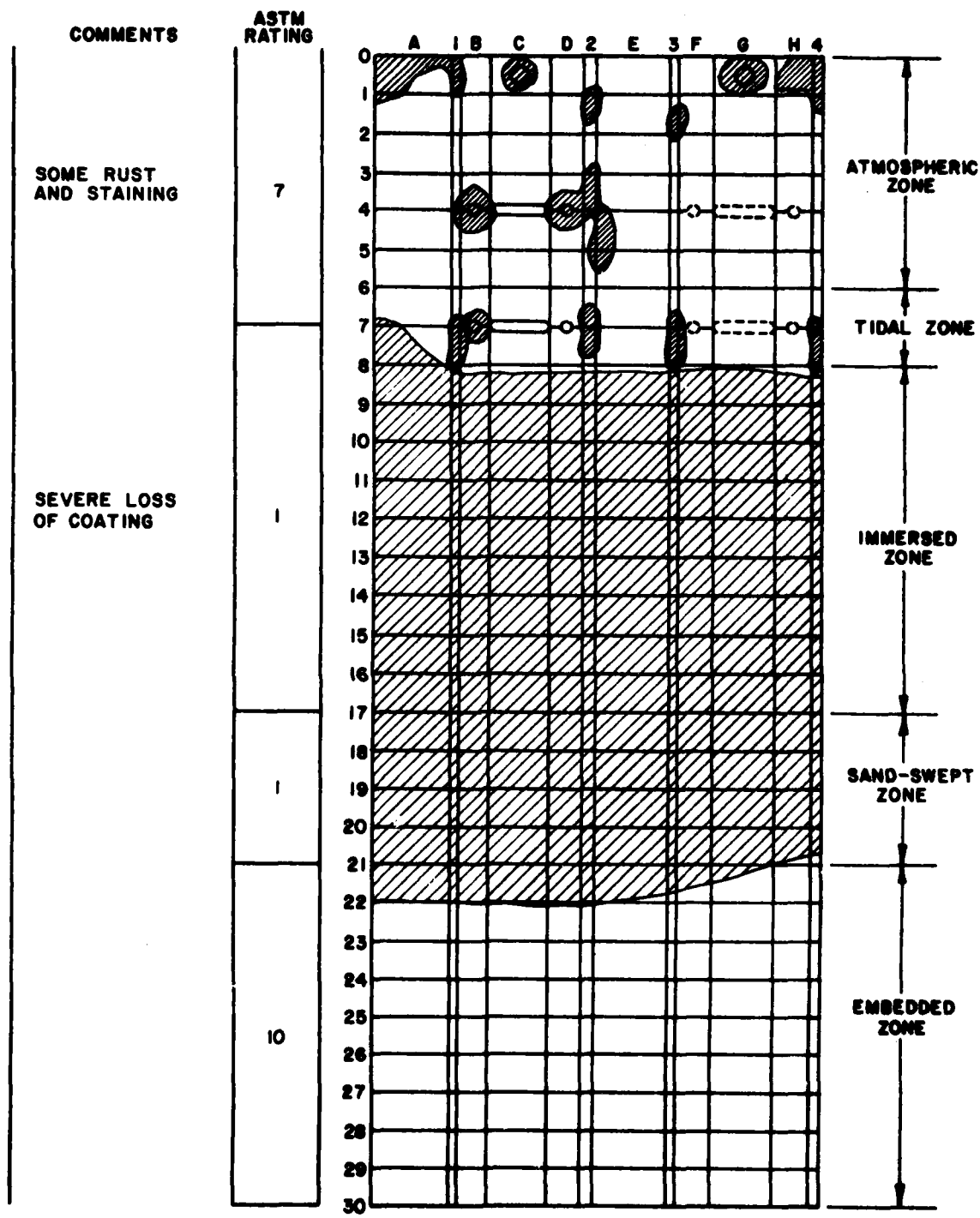
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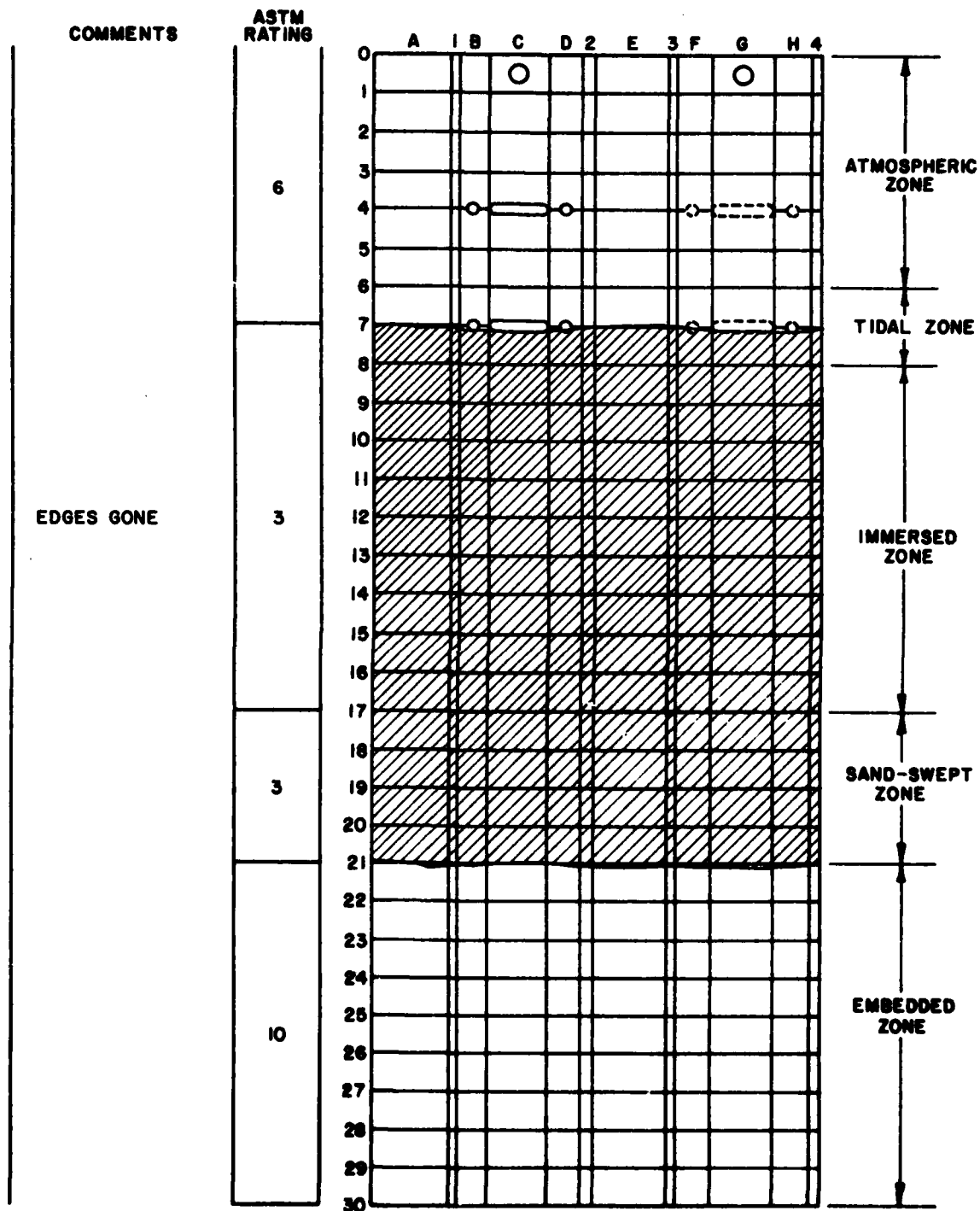
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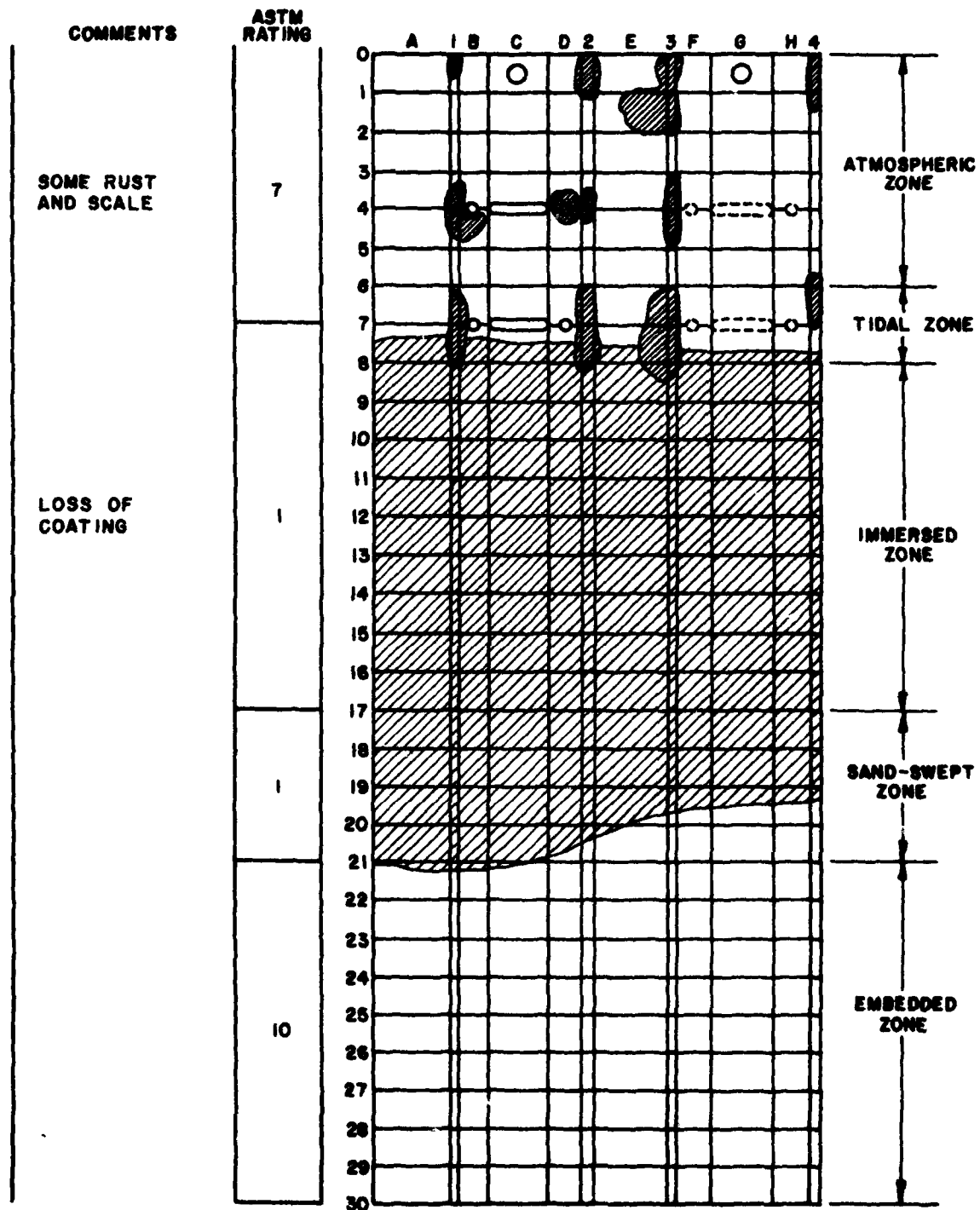
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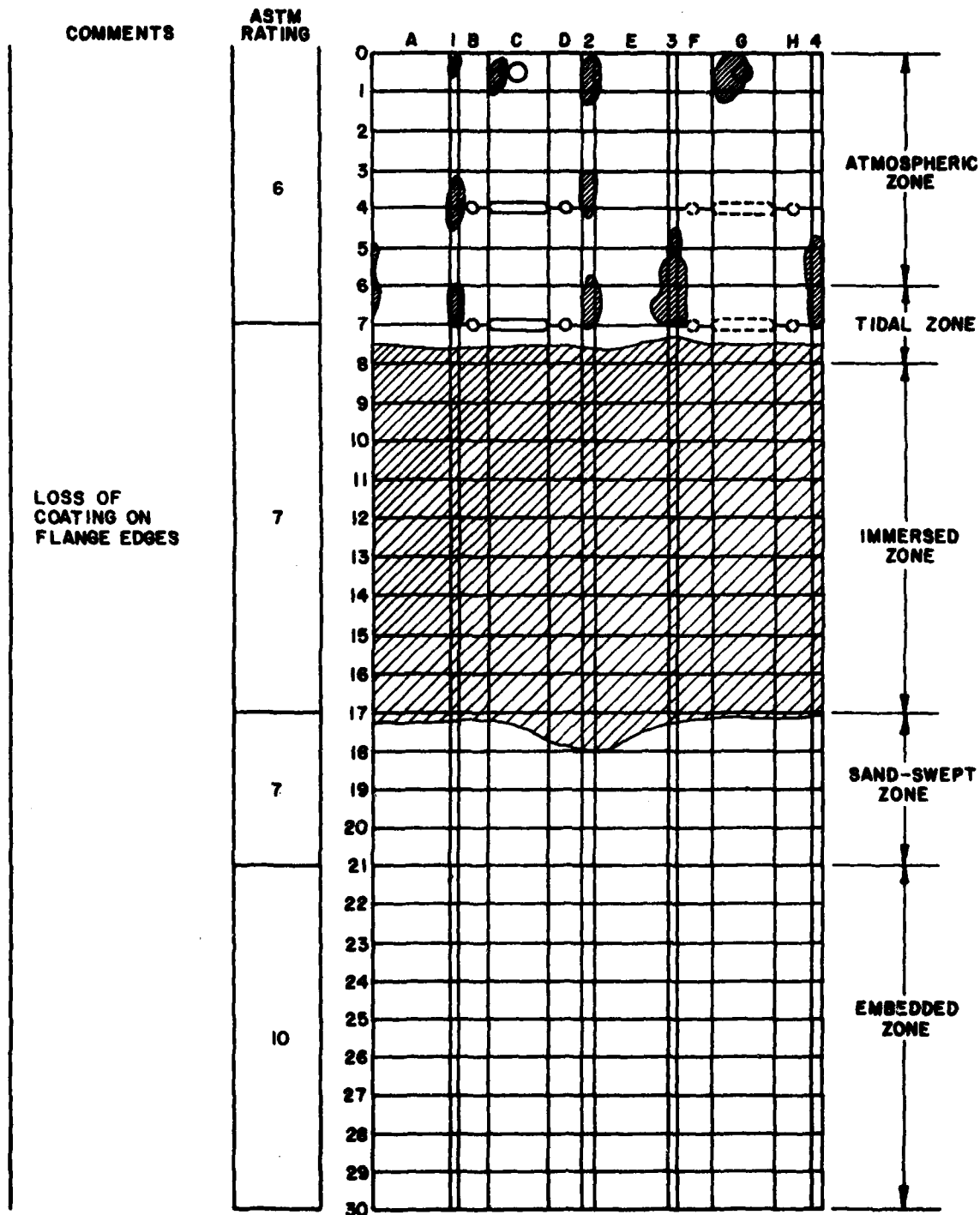
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→ SHOWS RUSTING



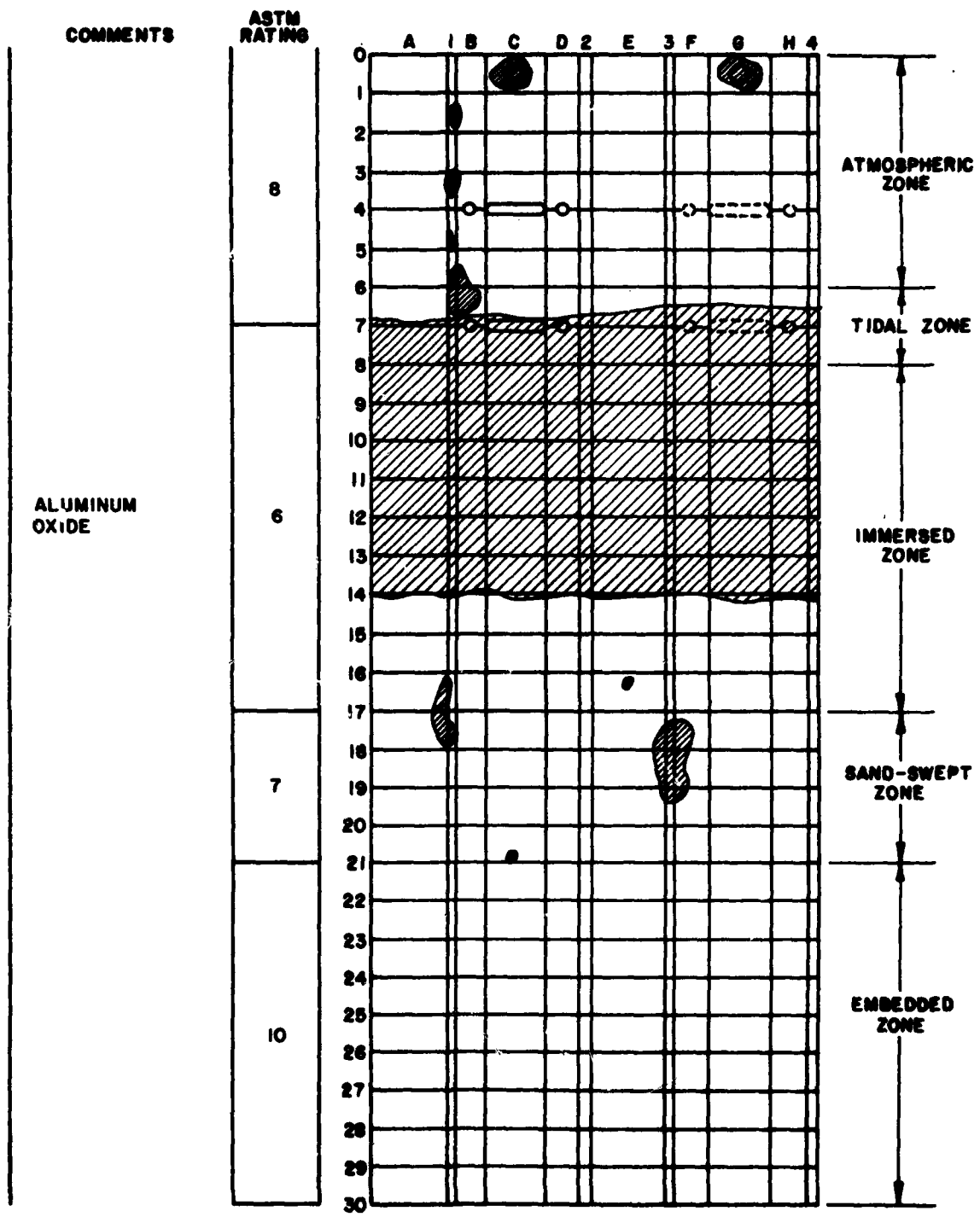
PILE NO. 68

→ SHOWS RUSTING



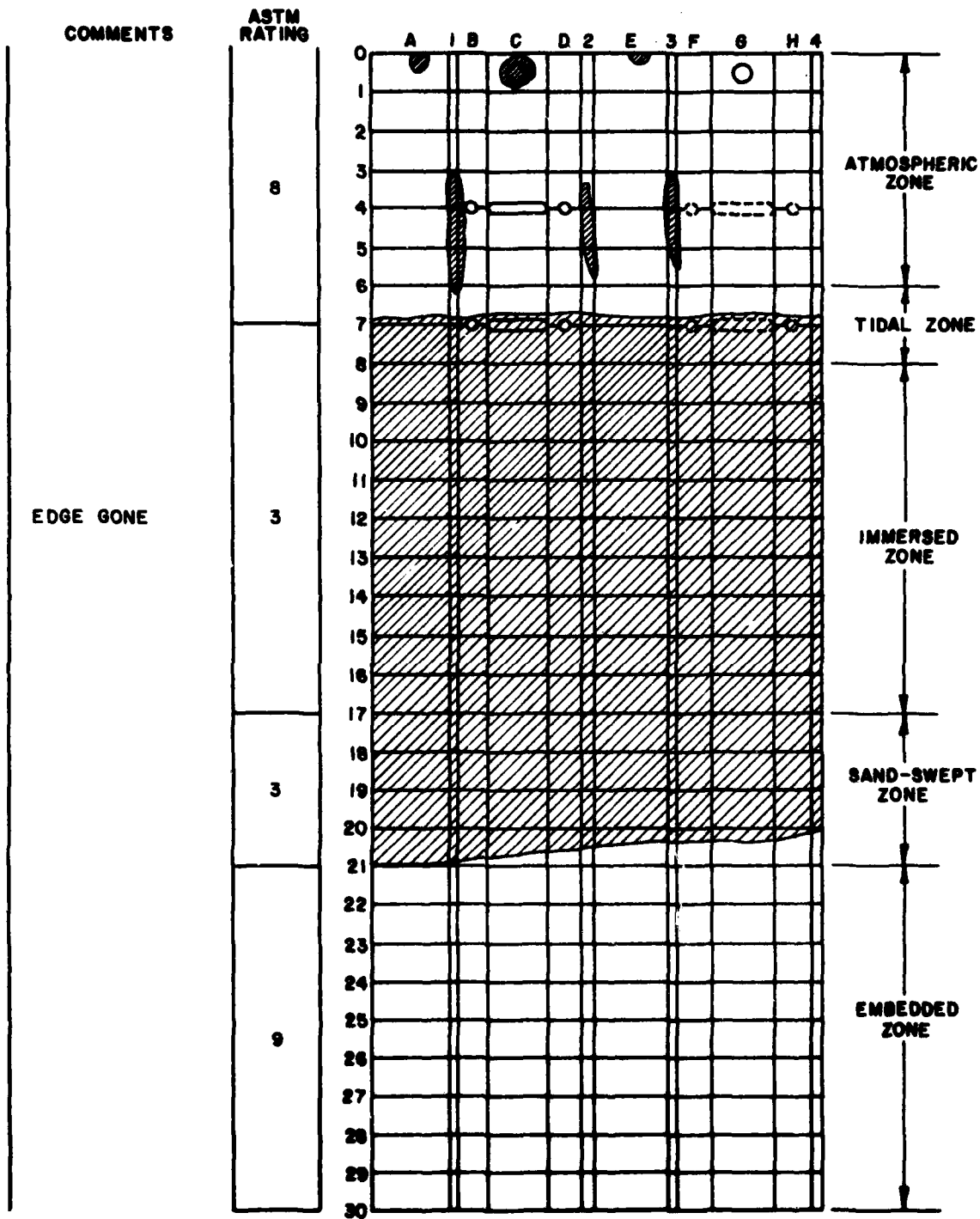
PILE NO. 7A

— SHOWS RUSTING



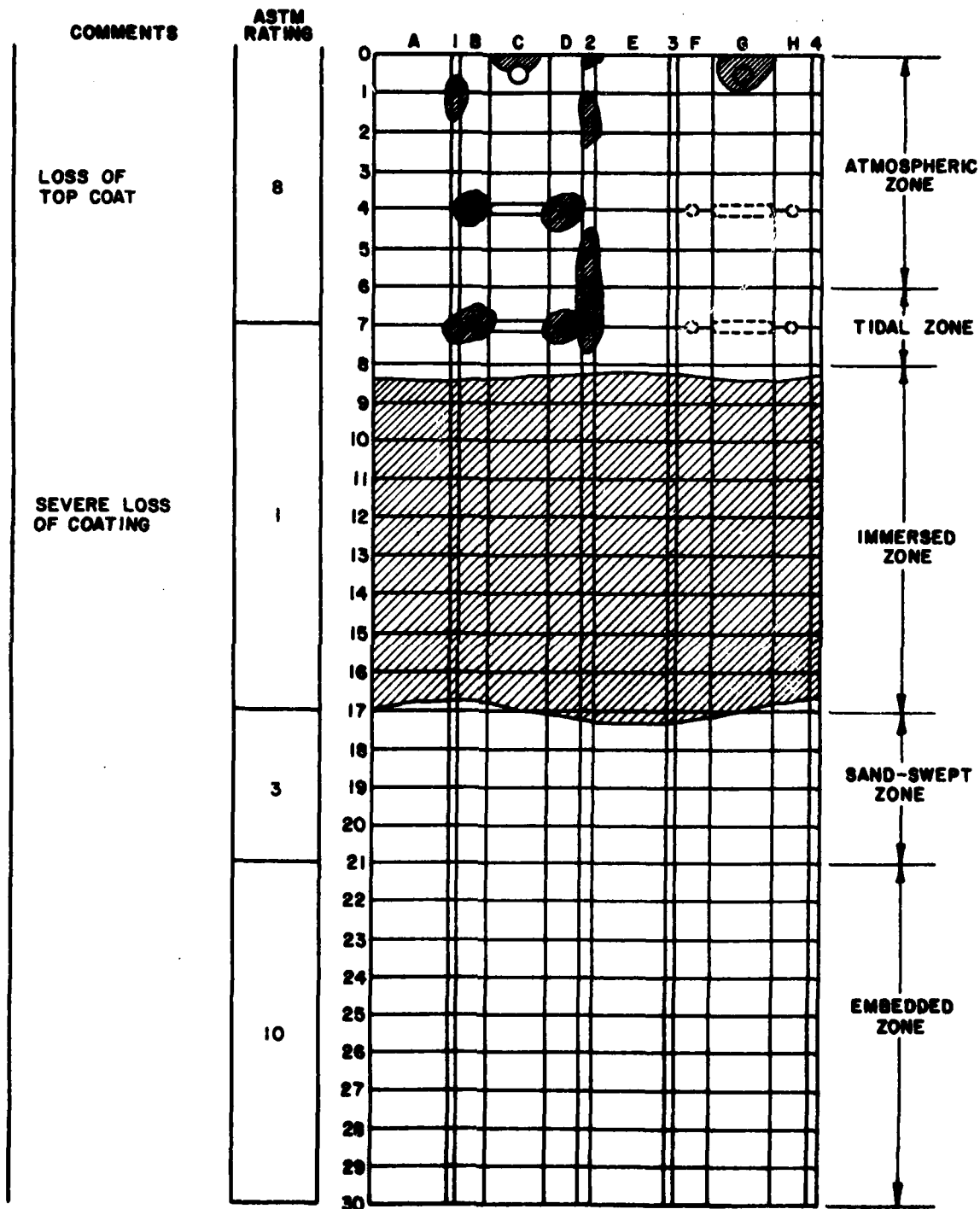
FILE NO. 7B

— SHOWS RUSTING



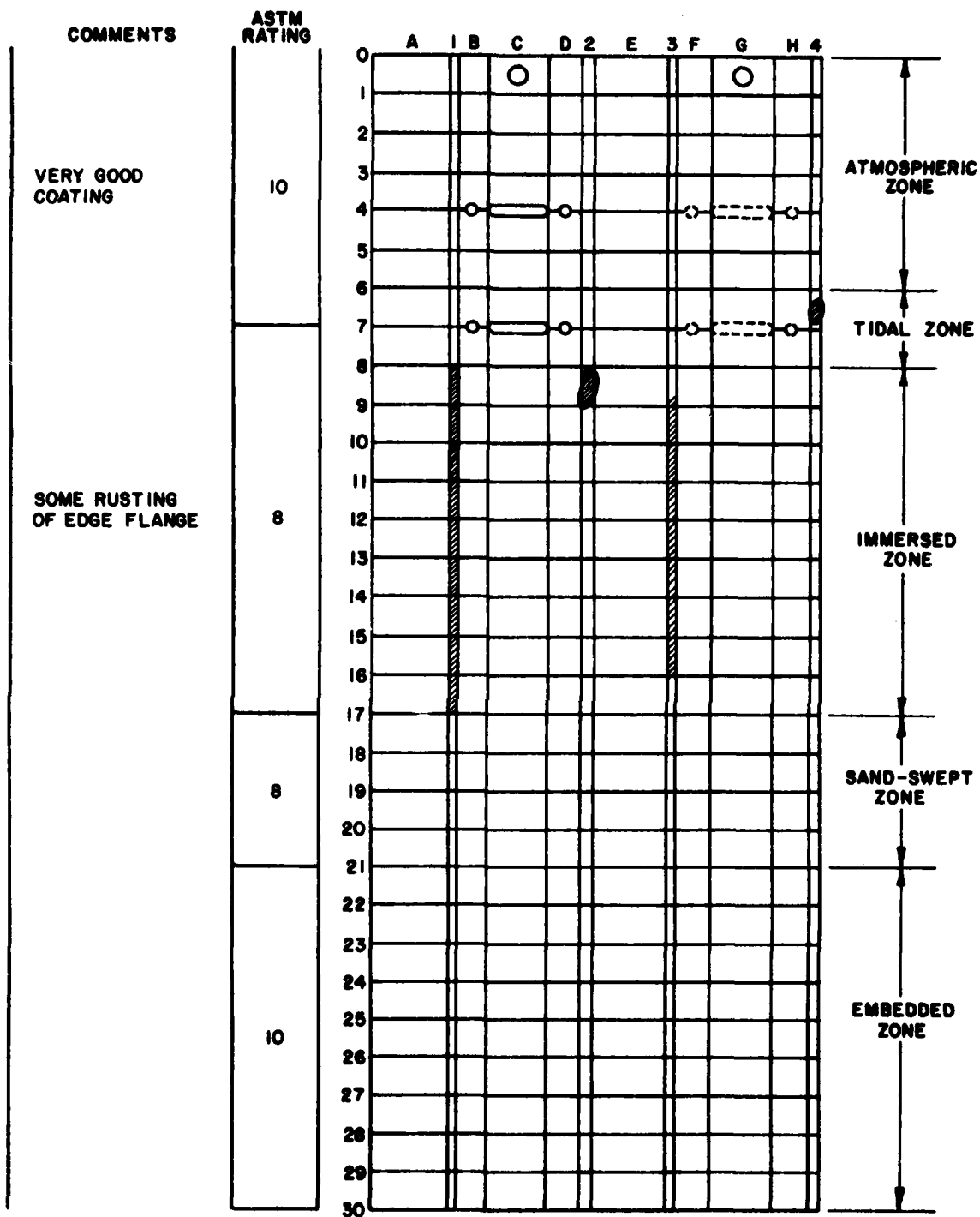
PILE NO. 8A

— SHOWS RUSTING



PILE NO. 88

→ SHOWS RUSTING



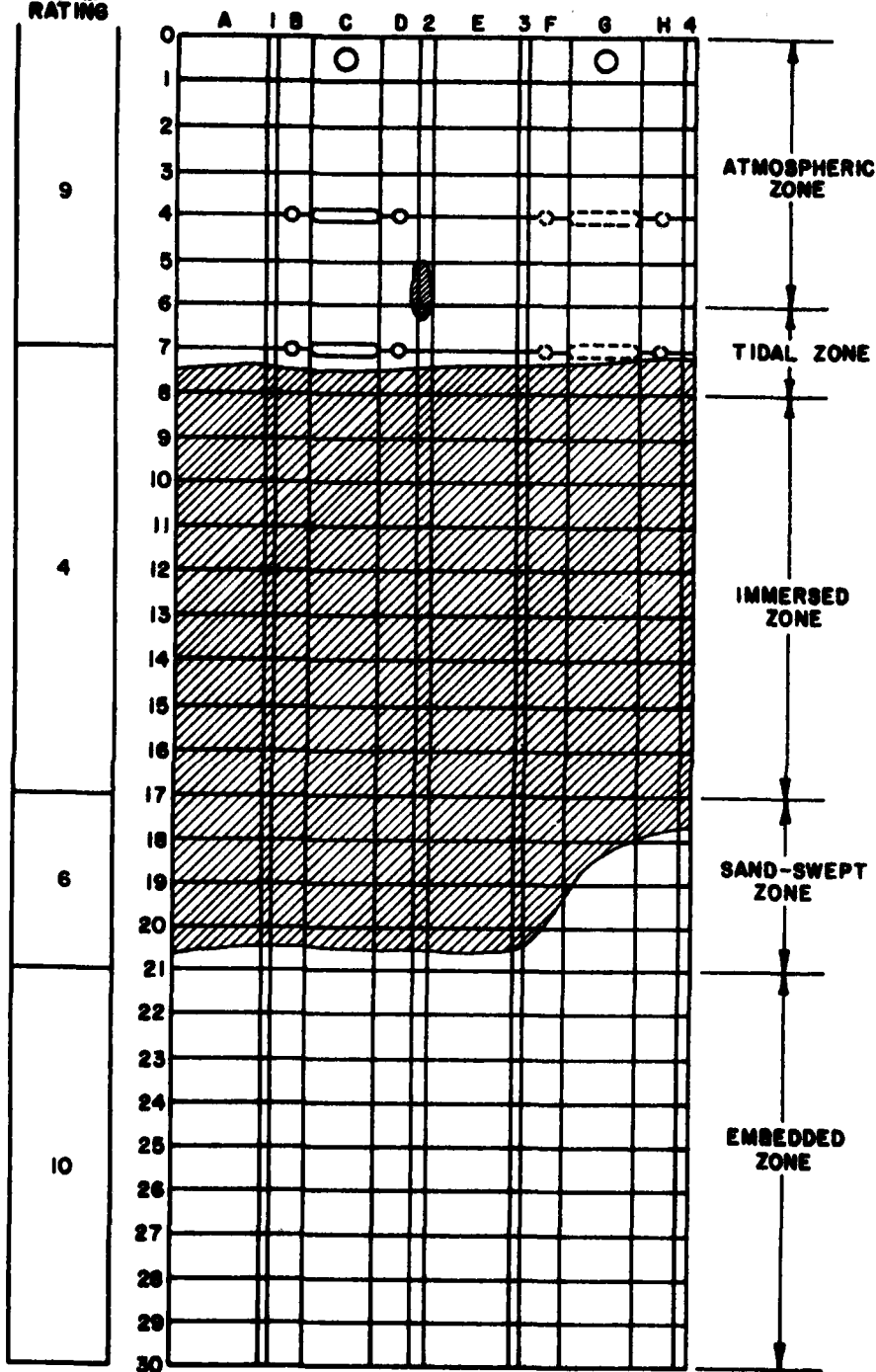
PILE NO. 9A

 → SHOWS RUSTING

COMMENTS

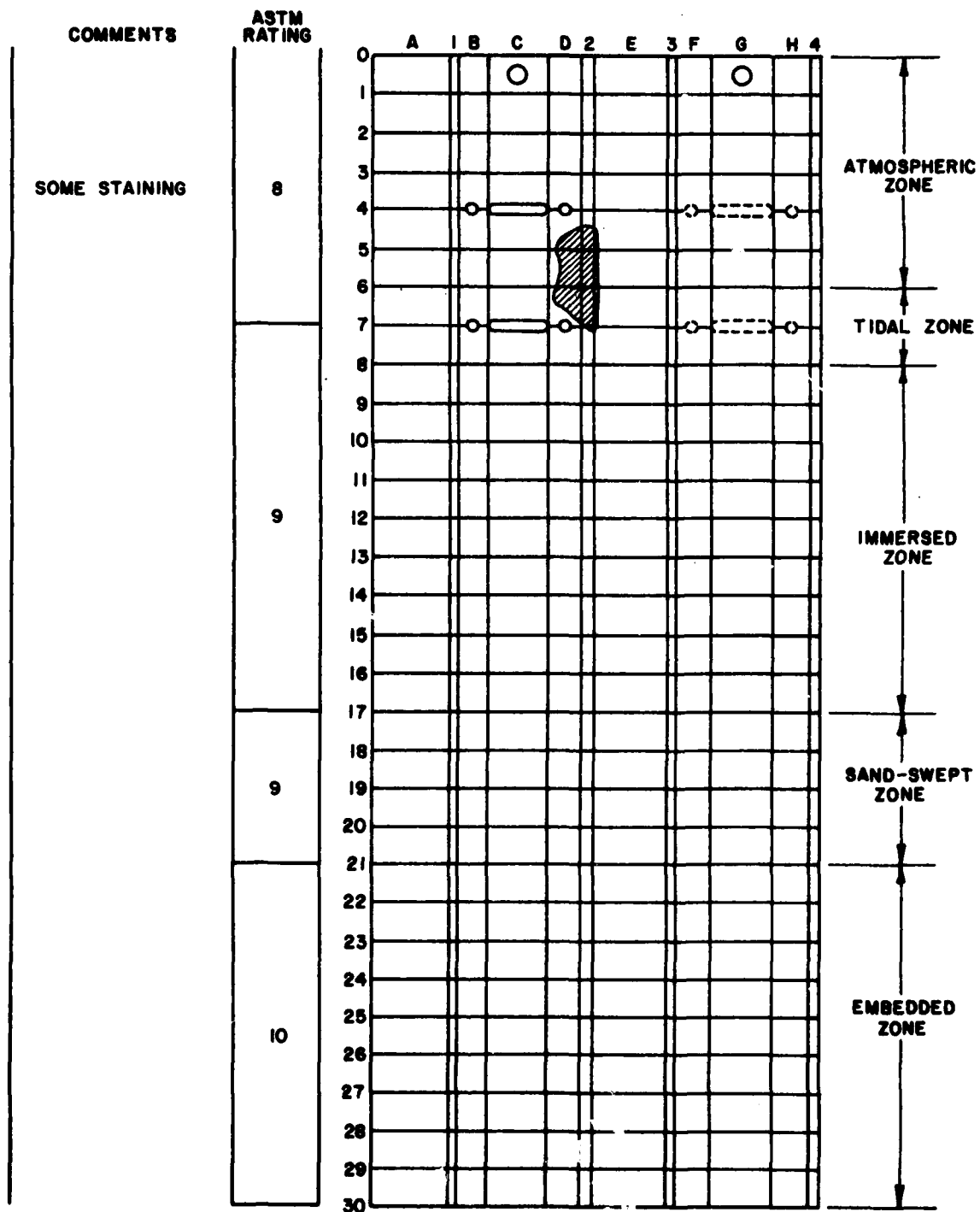
ASTM
RATING

EDGE IS
EXTREMELY
CORRODED



PILE NO. 9B

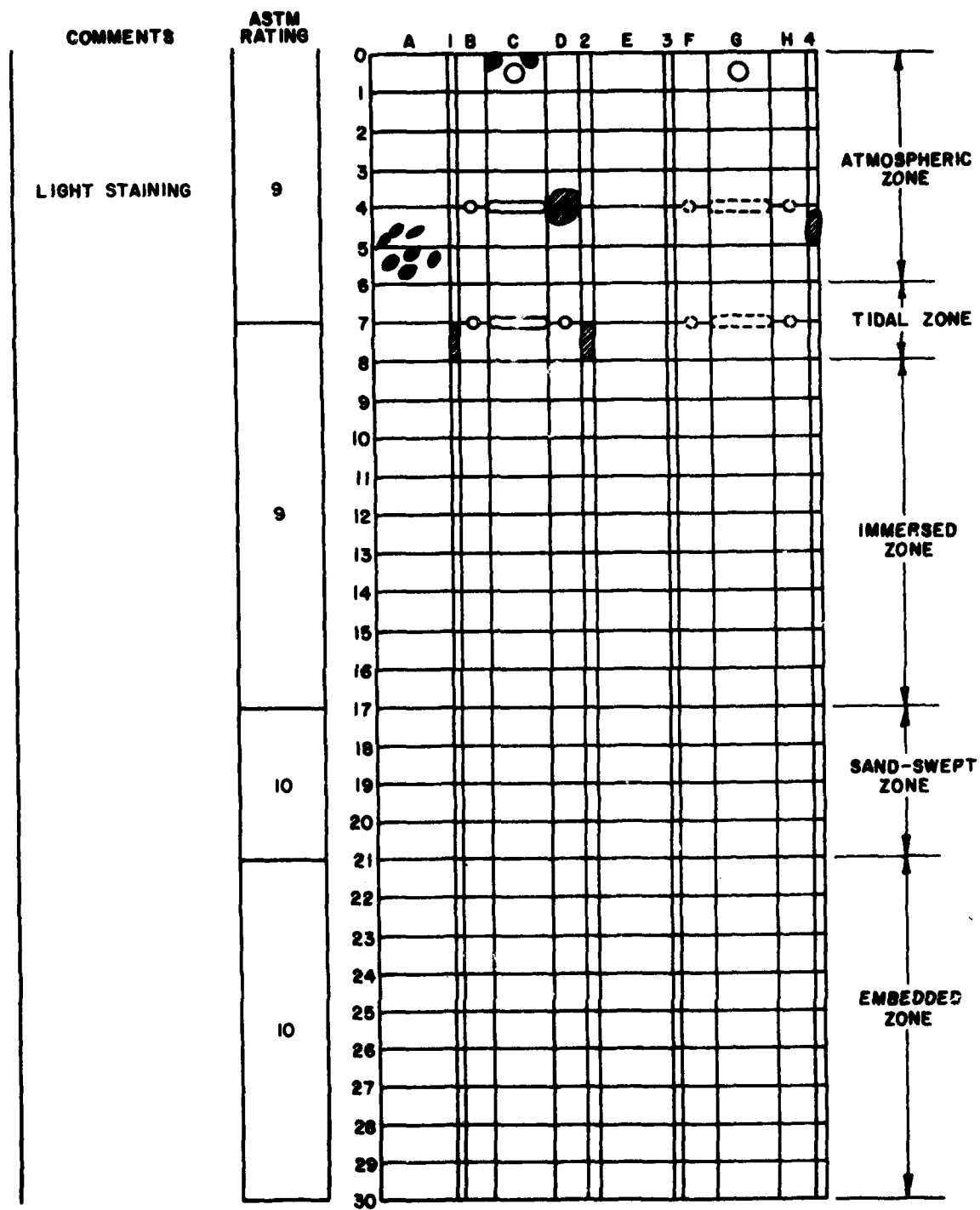
→ SHOWS RUSTING



PILE NO. 10A

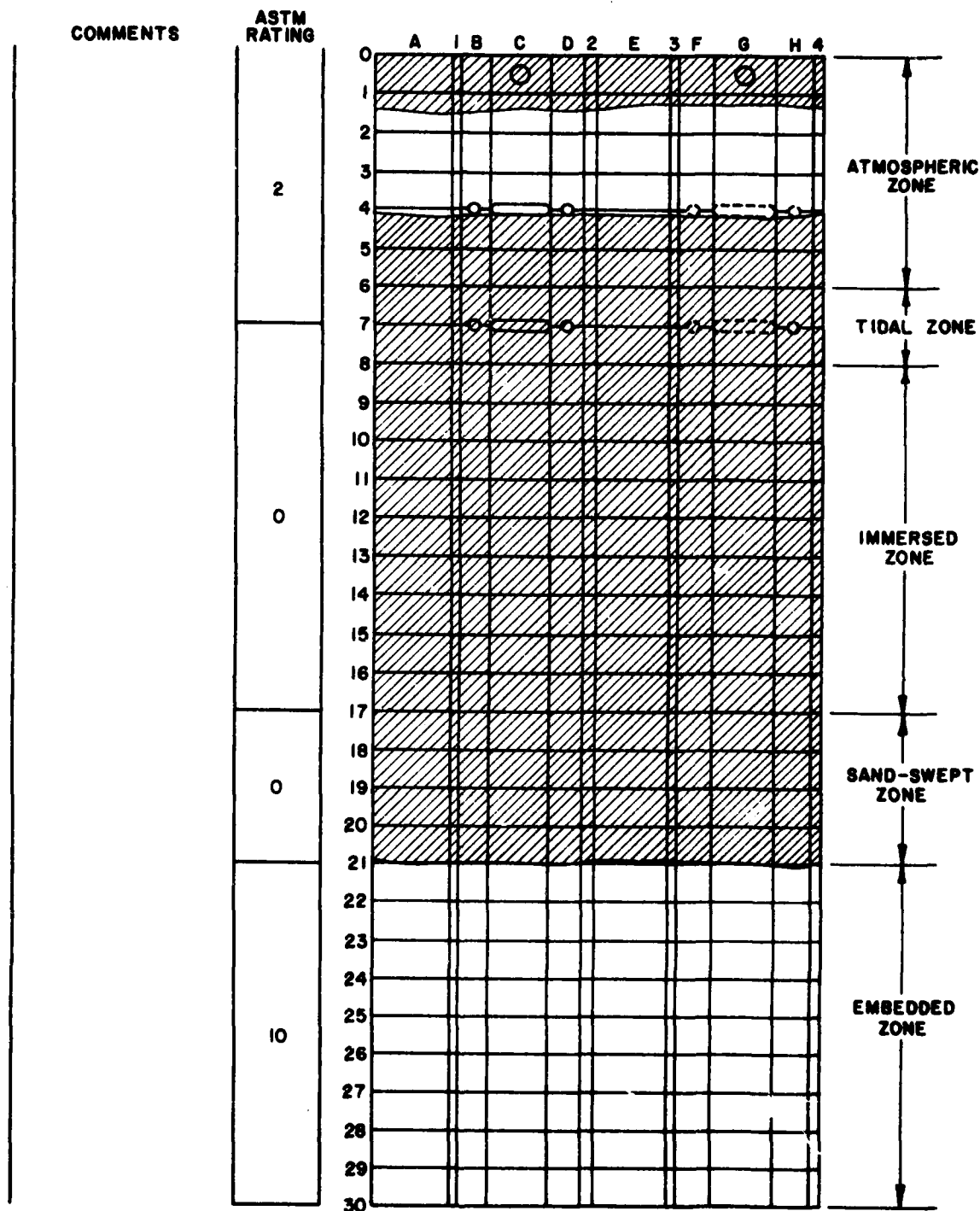


SHOWS RUSTING



PILE NO. 10B

→ SHOWS RUSTING

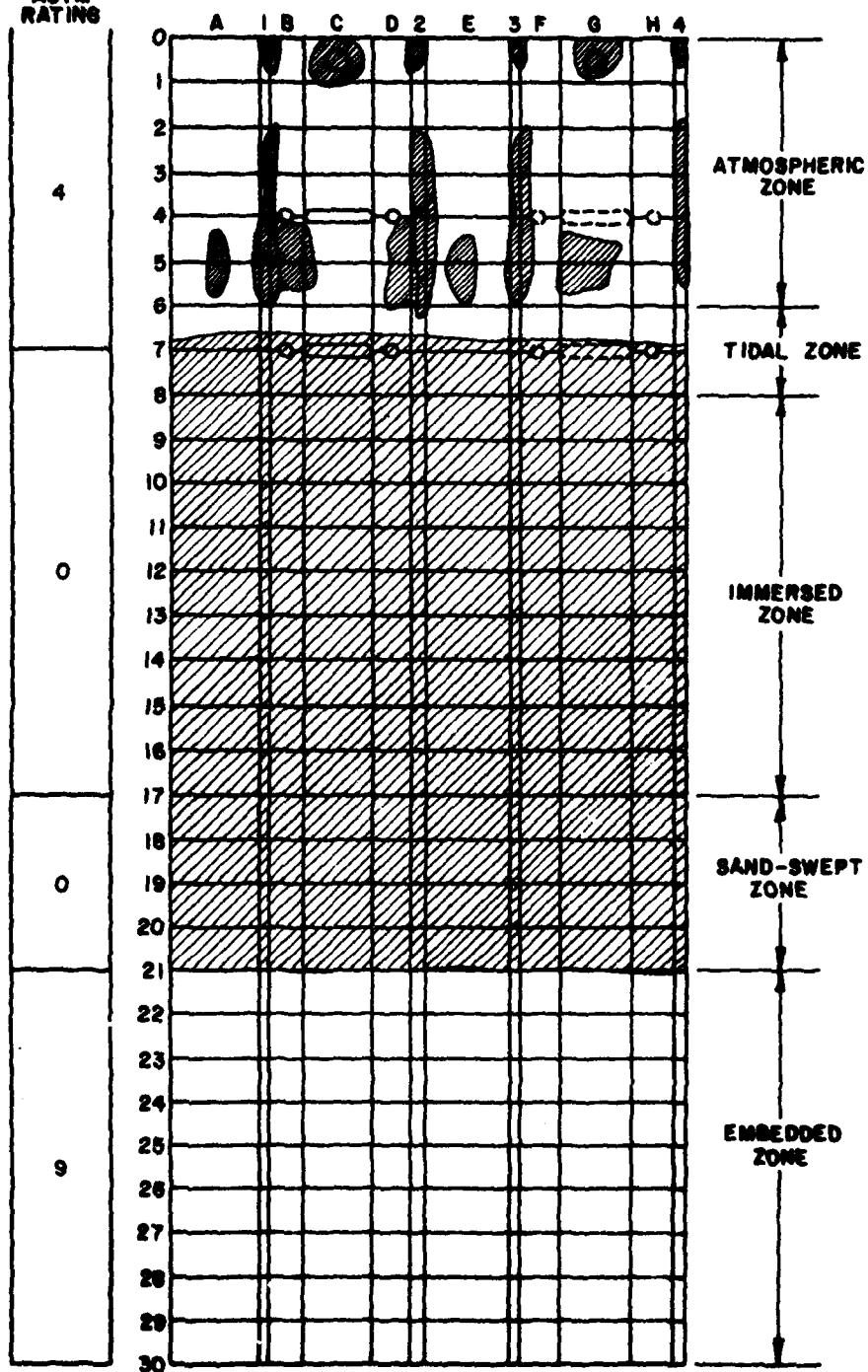


PILE NO. 11A

 → SHOWS RUSTING

COMMENTS

ASTM
RATING

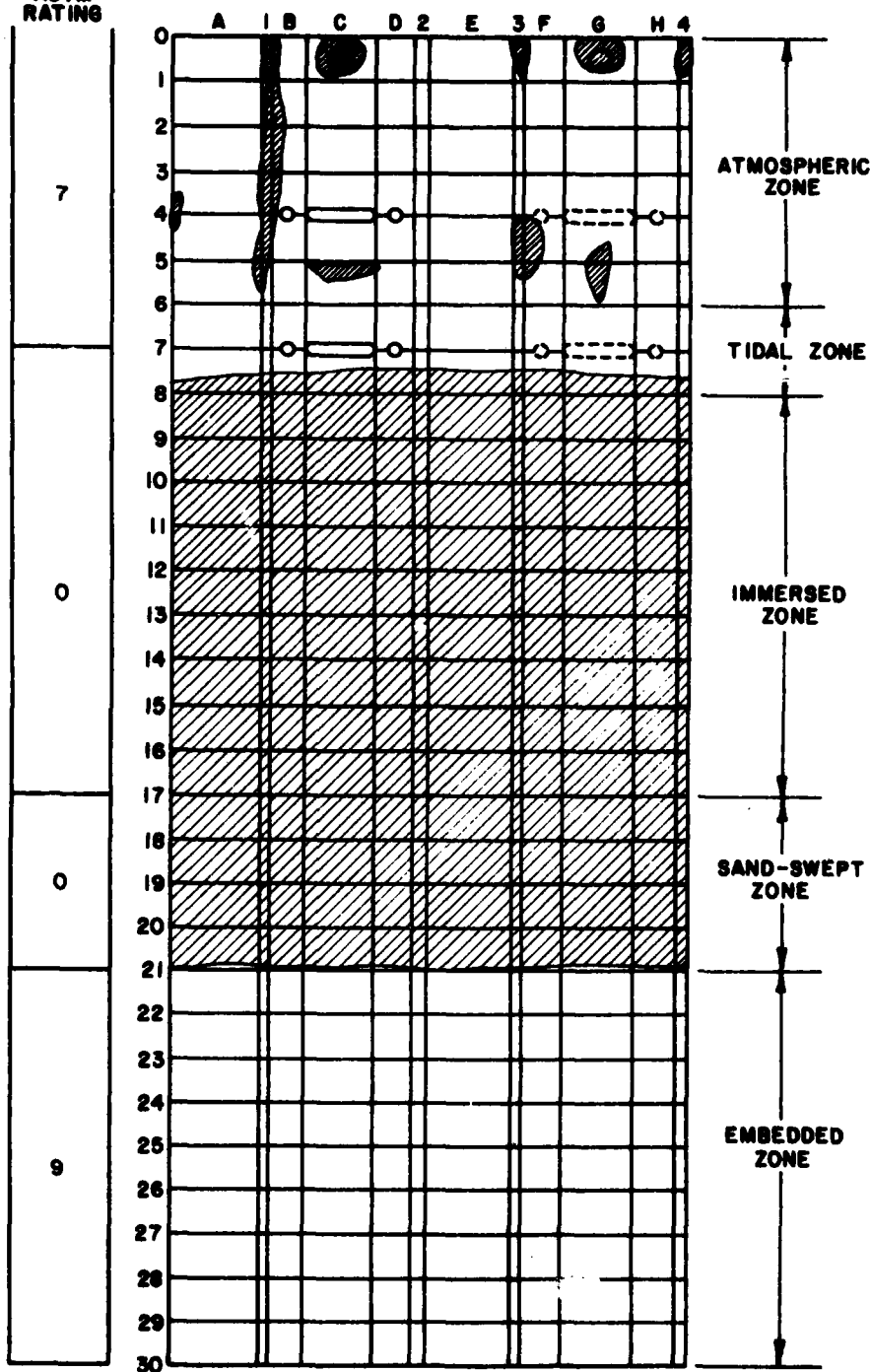


PILE NO. 11B

→ SHOWS RUSTING

COMMENTS

ASTM
RATING

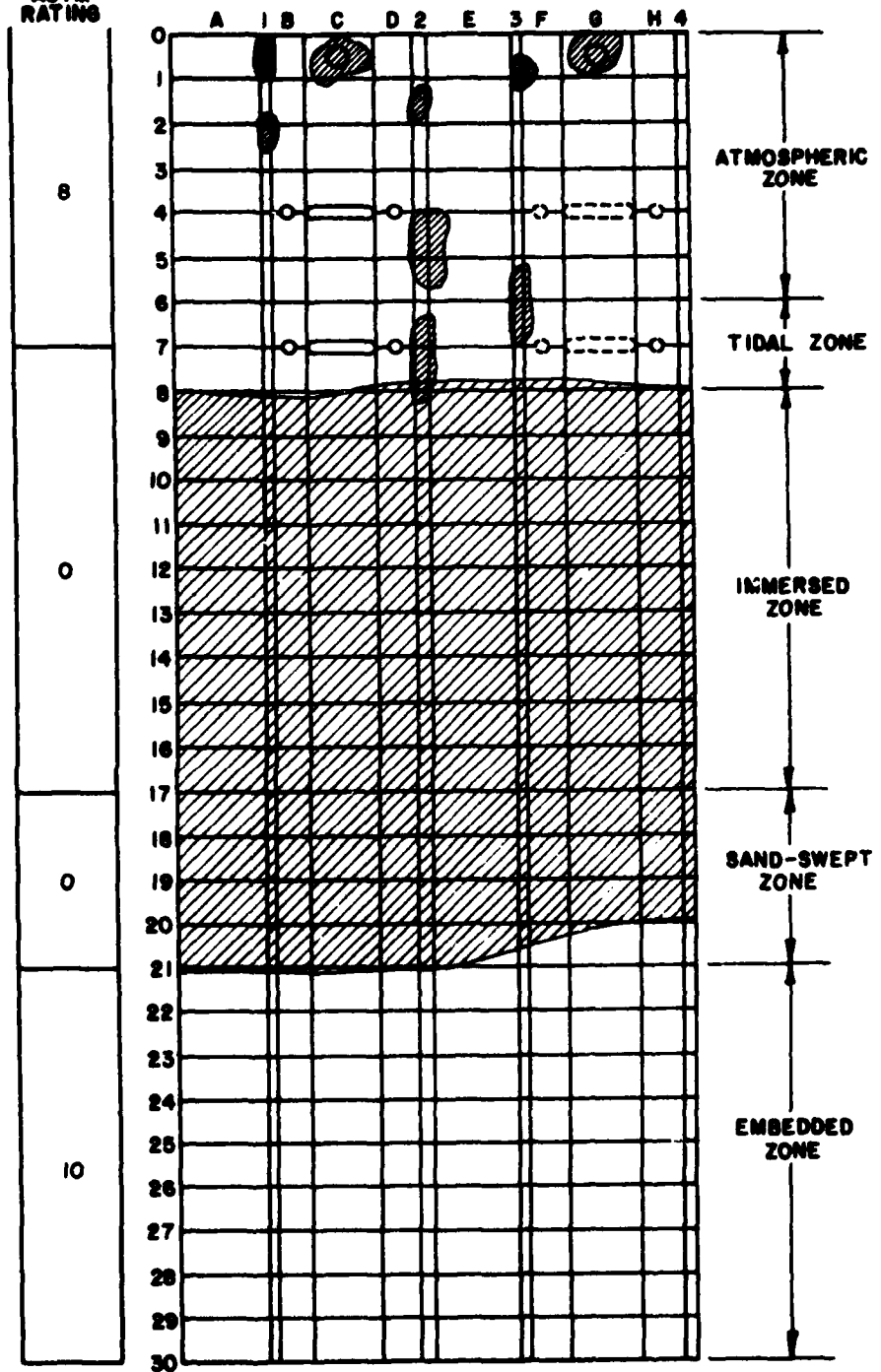


PILE NO. 12A

→ SHOWS RUSTING

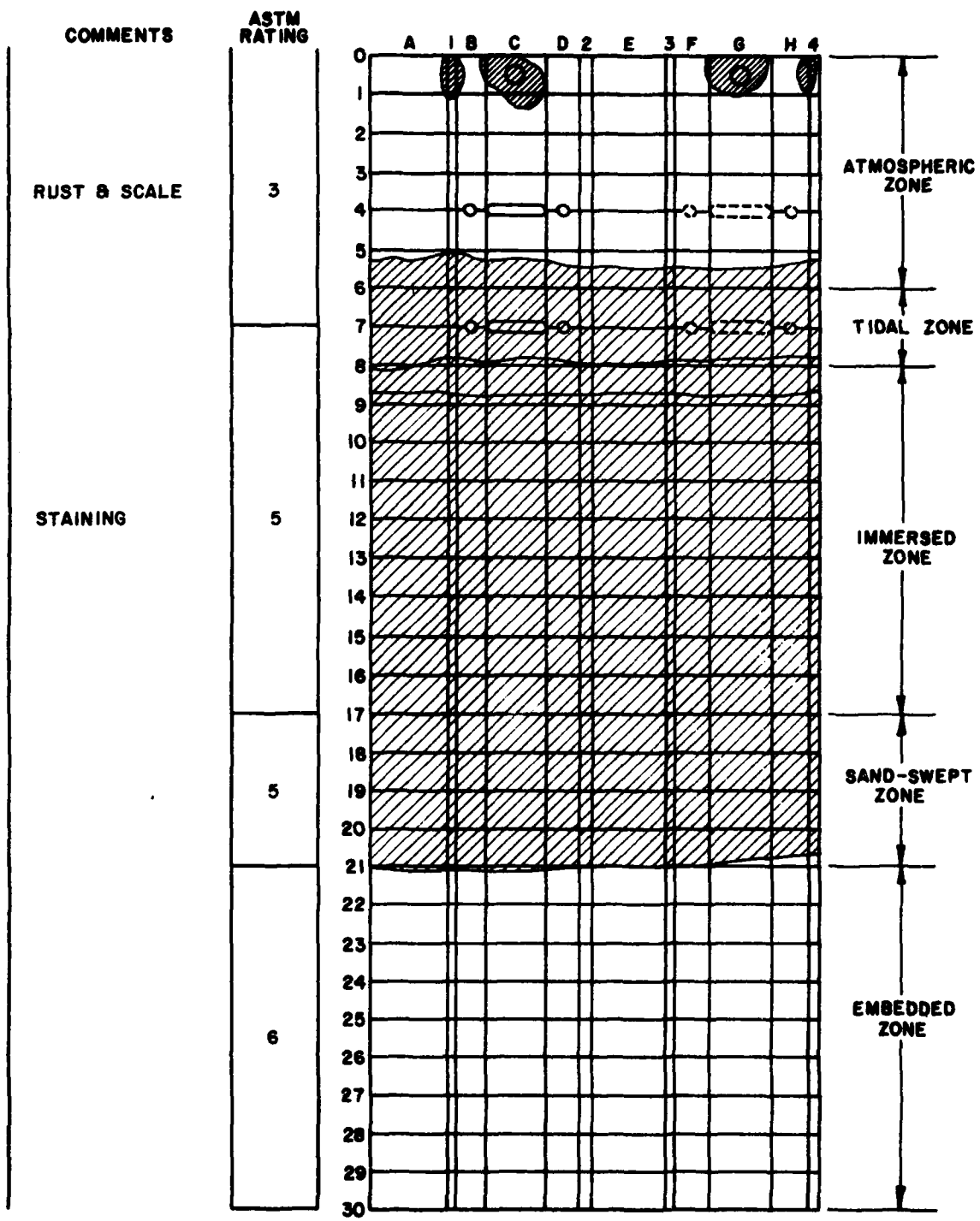
COMMENTS

ASTM
RATING



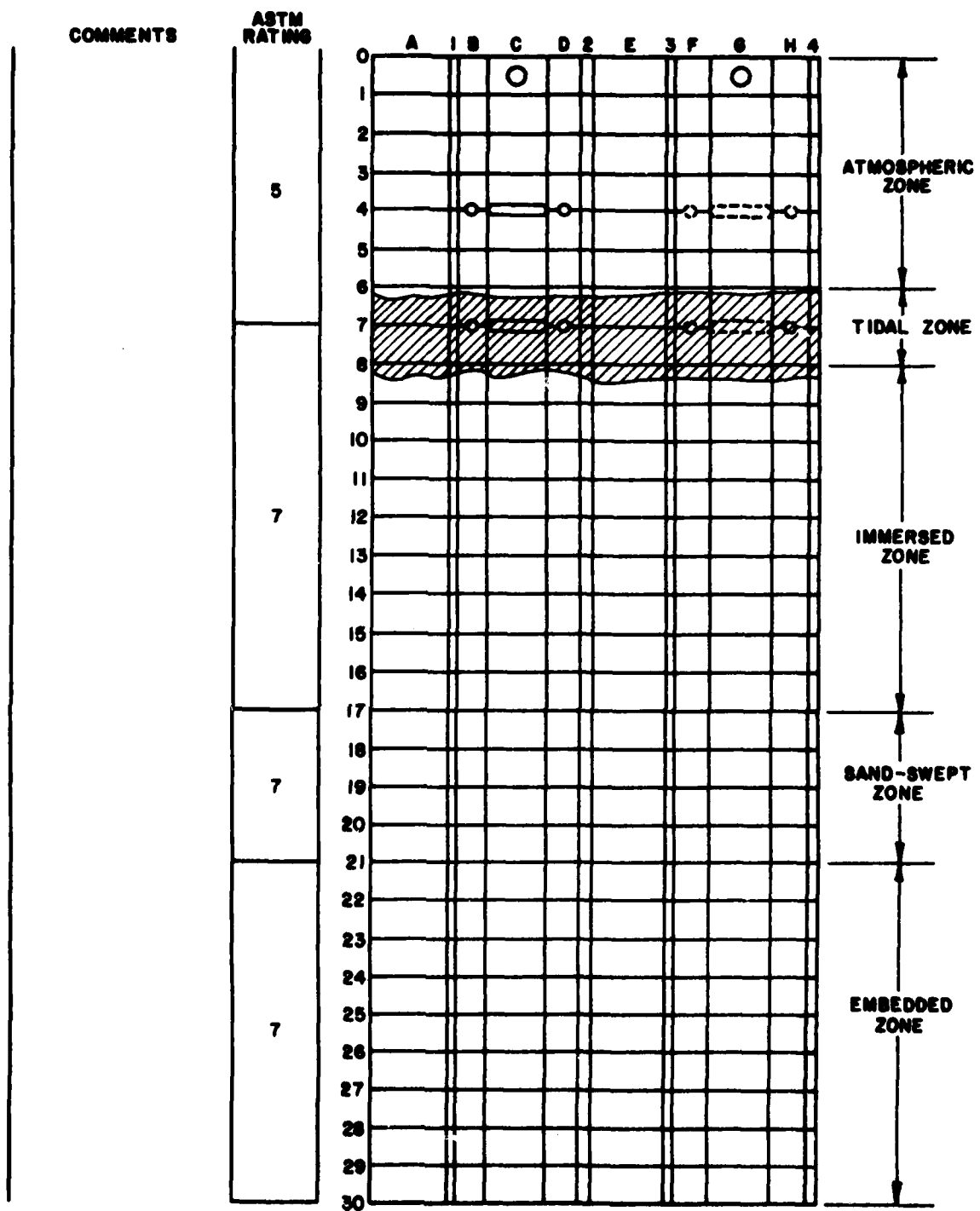
PILE NO. 128

→ SHOWS RUSTING



PILE NO. 13A

 → SHOWS RUSTING

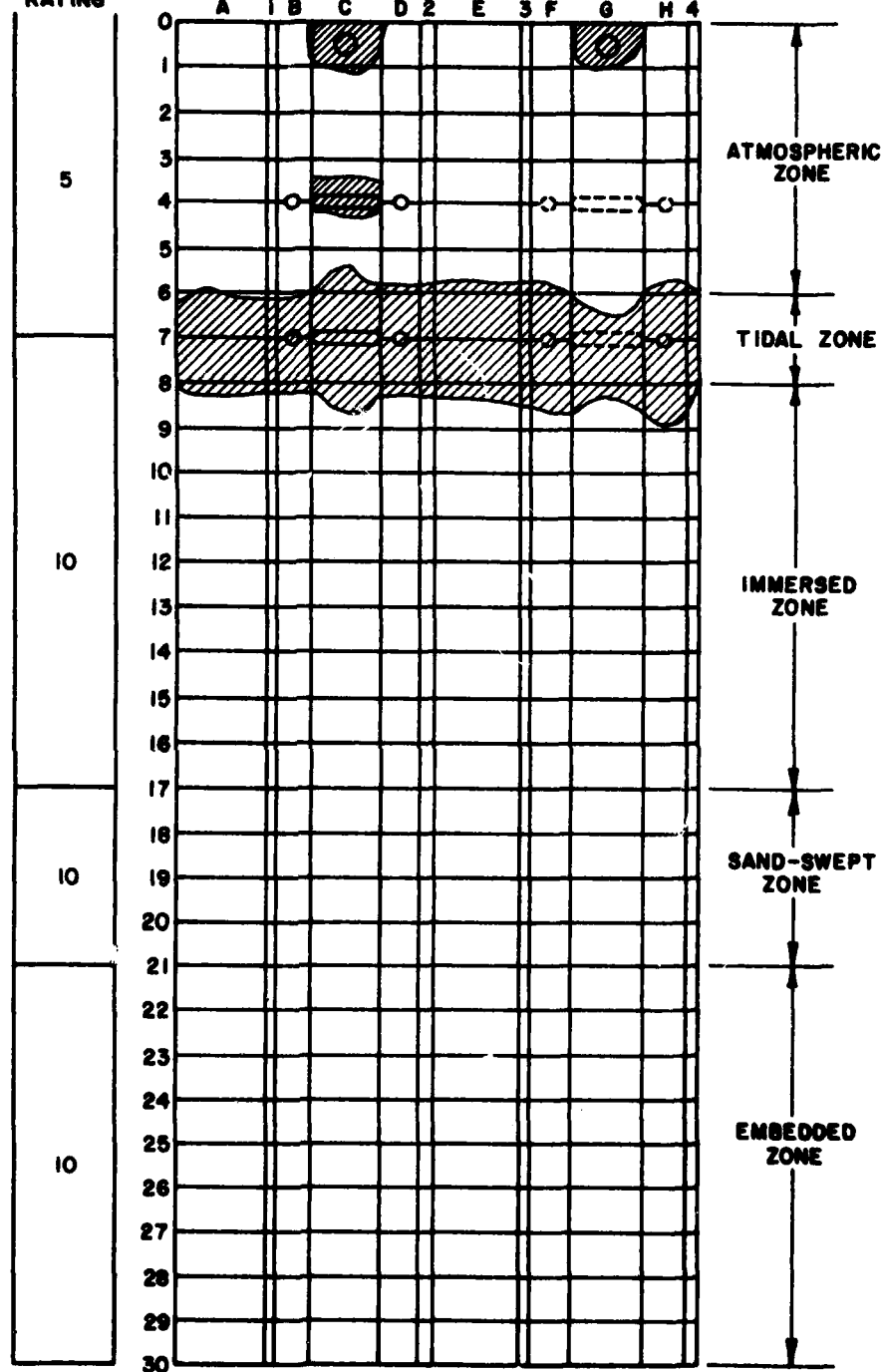


PILE NO. 13B

→ SHOWS RUSTING

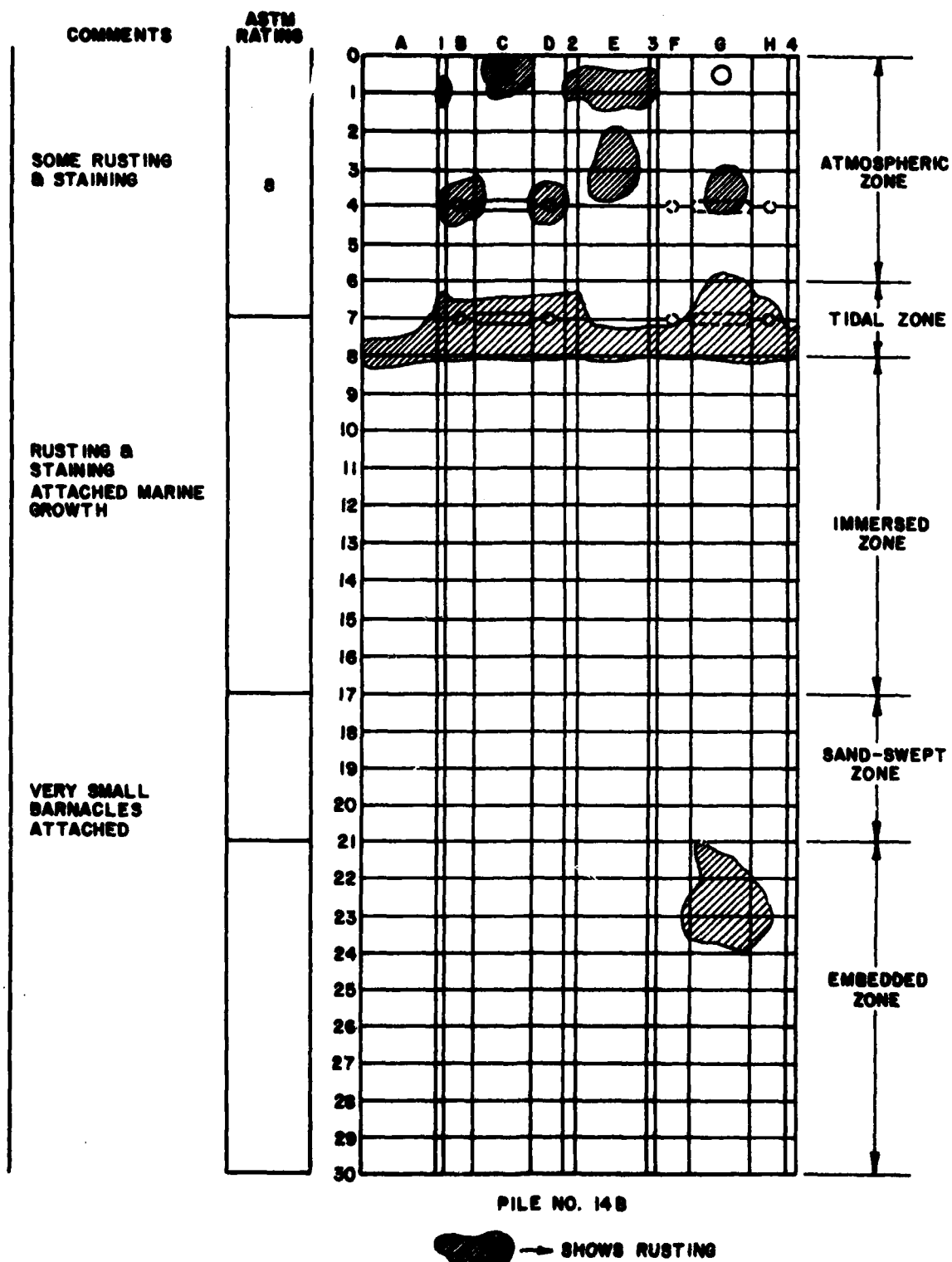
COMMENTS

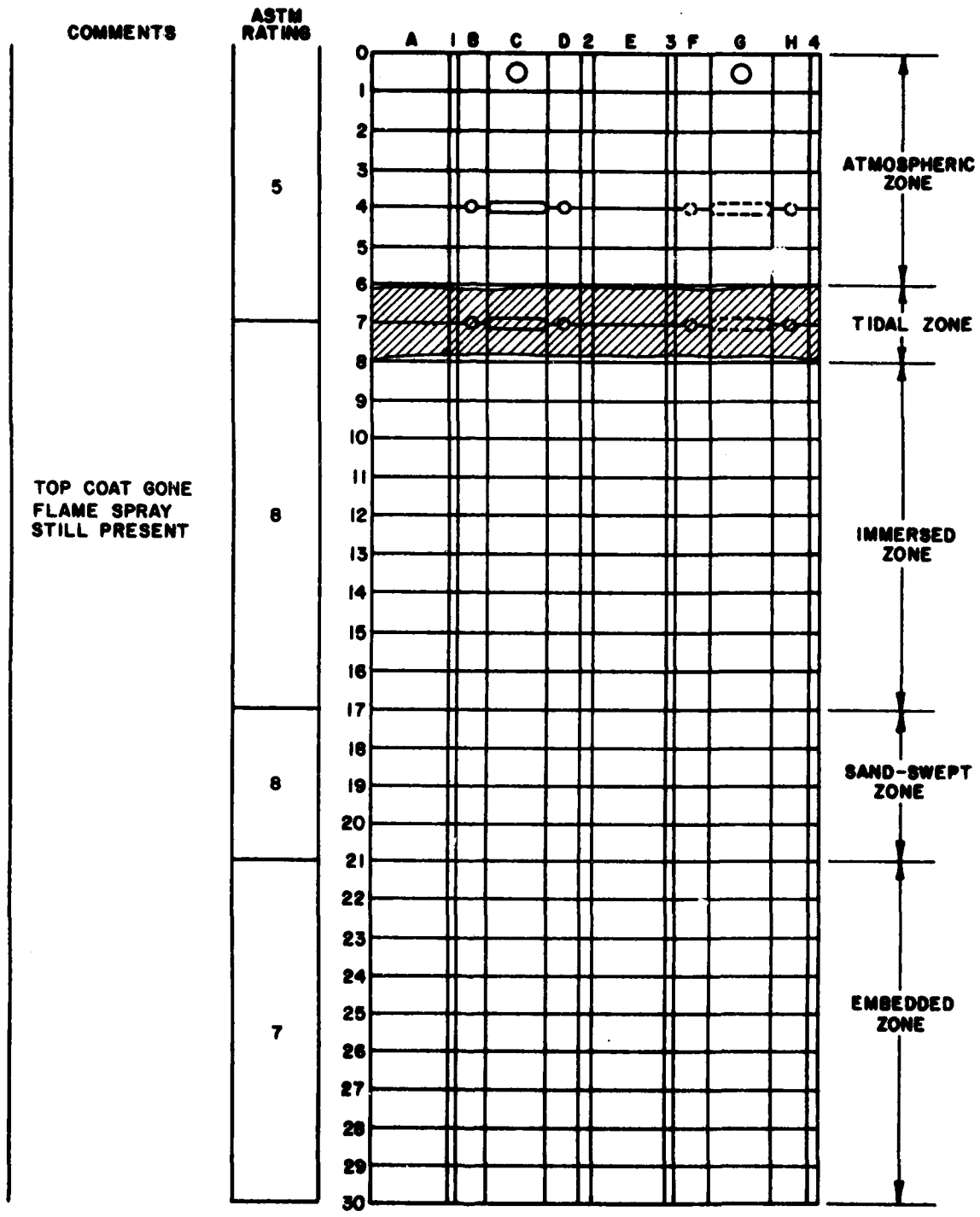
ASTM
RATING



PILE NO. 14A

 → SHOWS RUSTING





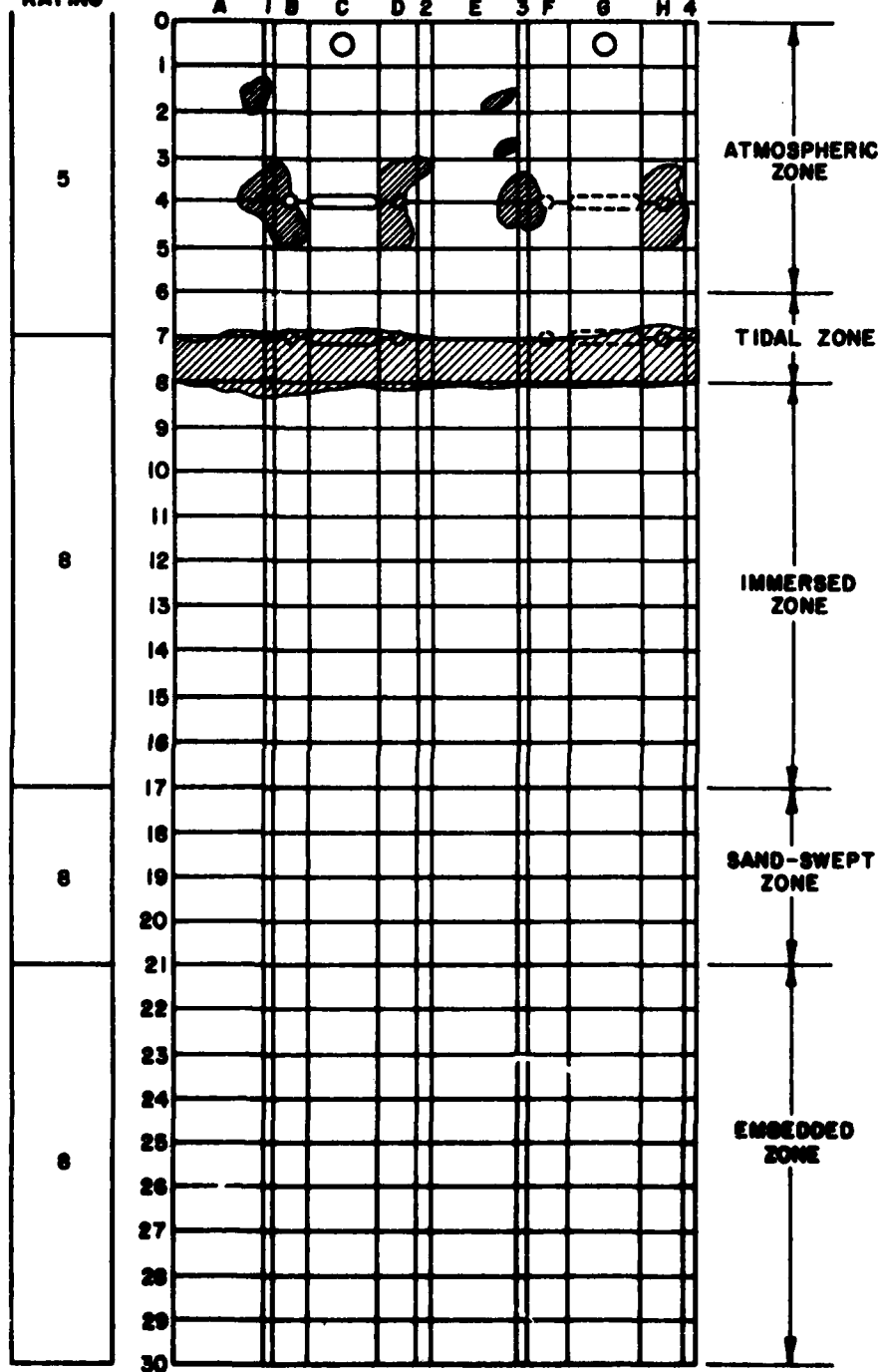
TOP COAT GONE
FLAME SPRAY
STILL PRESENT

PILE NO. 15A

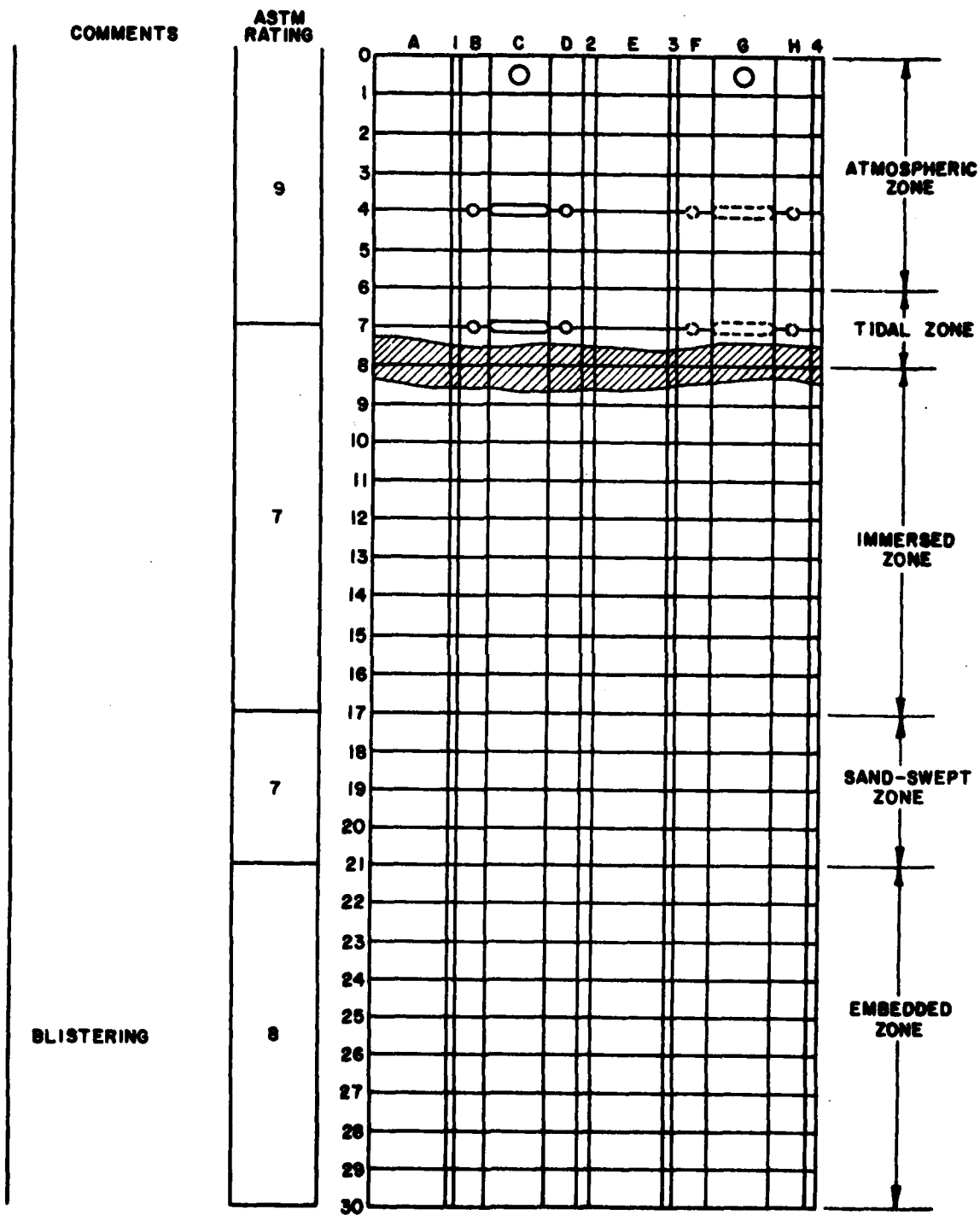
 → SHOWS RUSTING

COMMENTS

ASTM
RATING

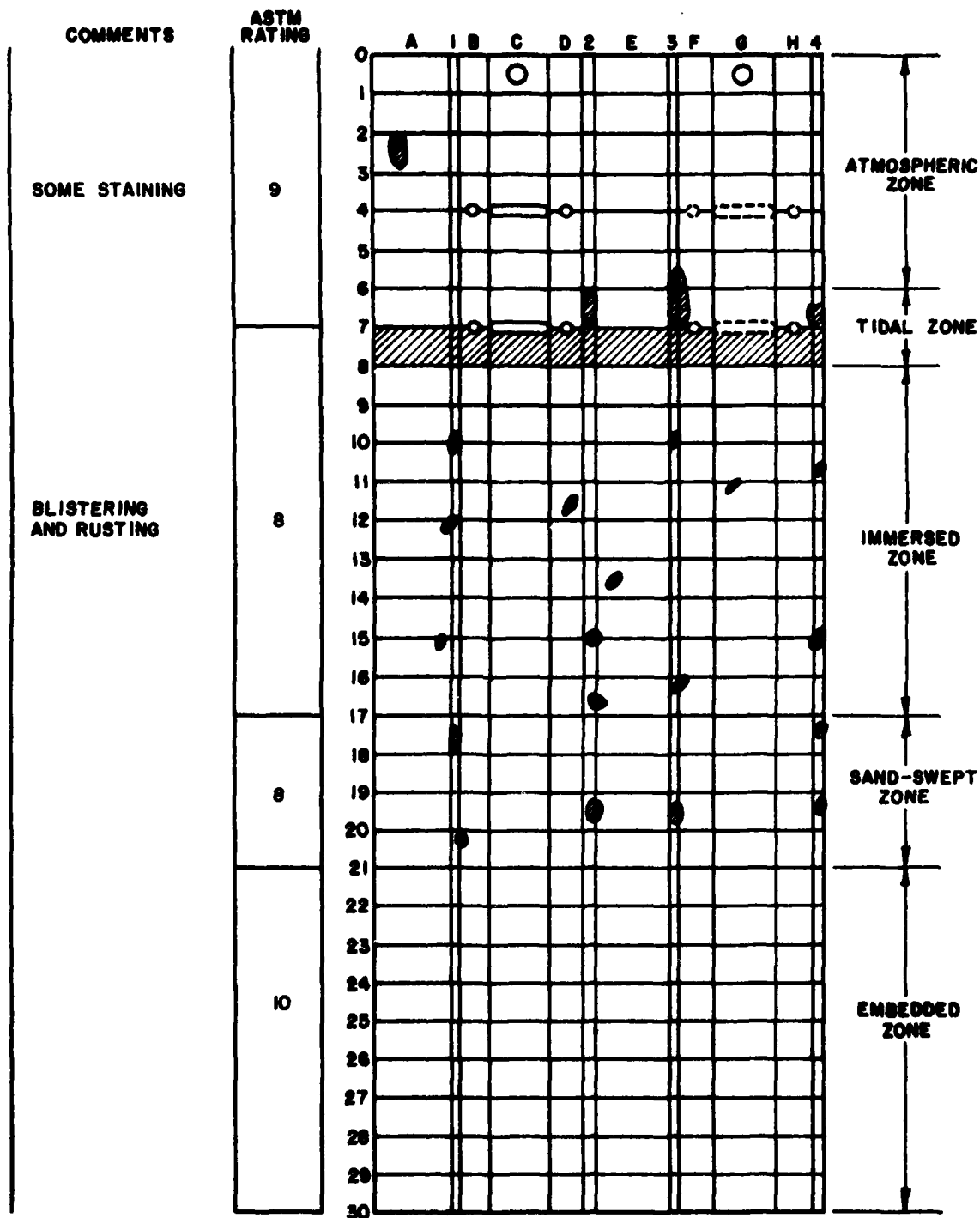


PILE NO. 15B



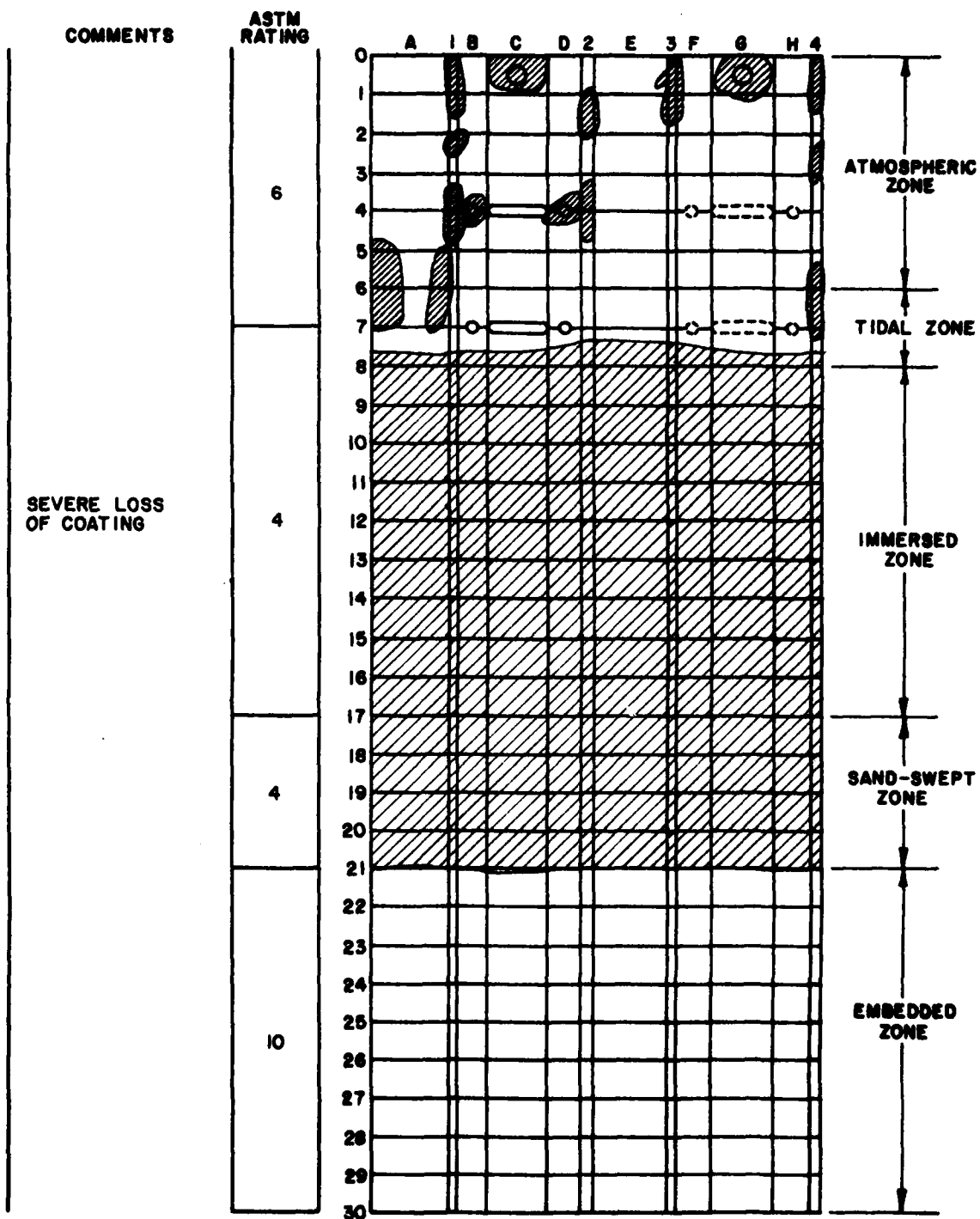
PILE NO. 16A

 → SHOWS RUSTING



PILE NO. 16B

● → SHOWS RUSTING

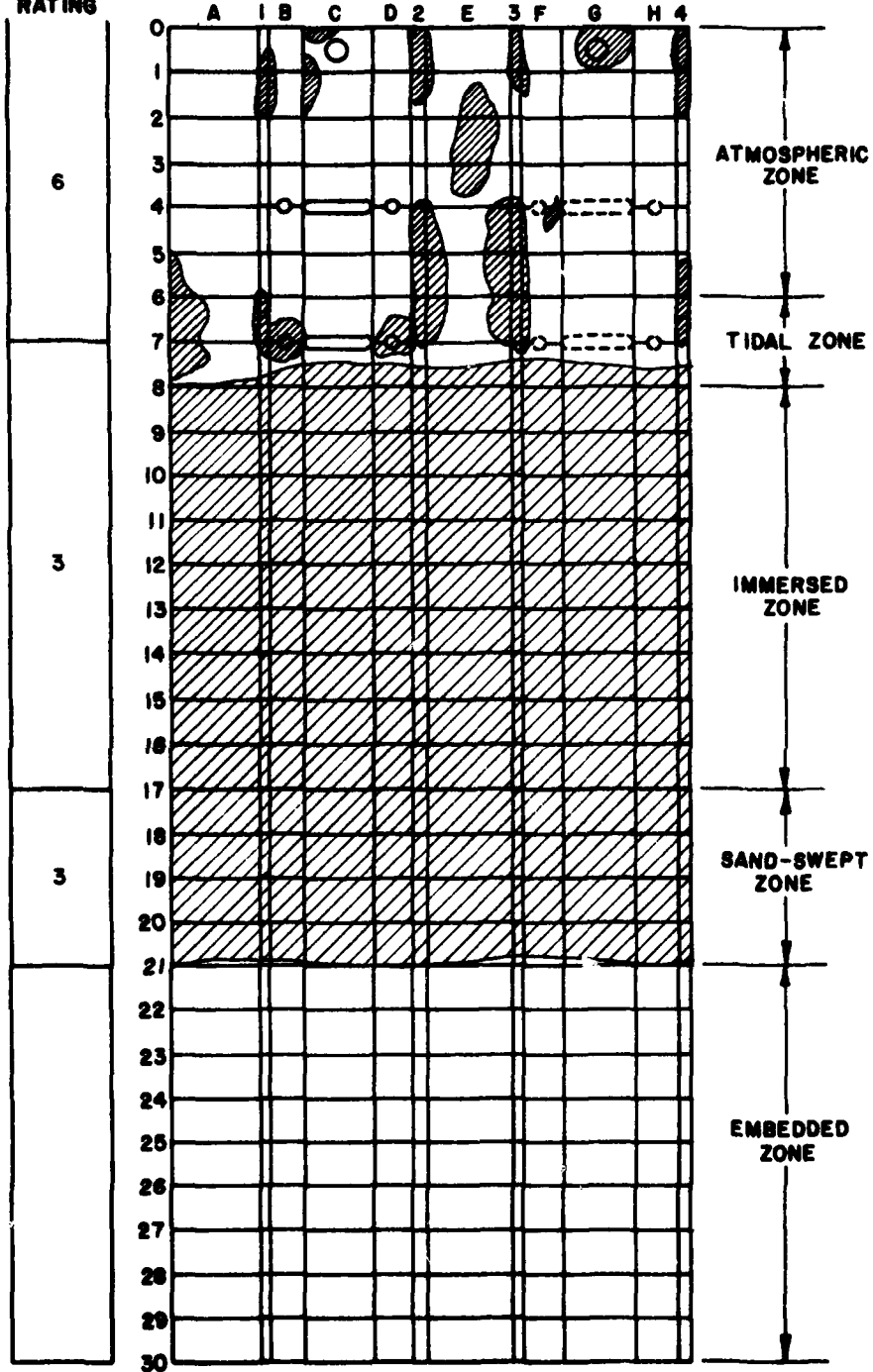


PILE NO. 17A

 → SHOWS RUSTING

COMMENTS

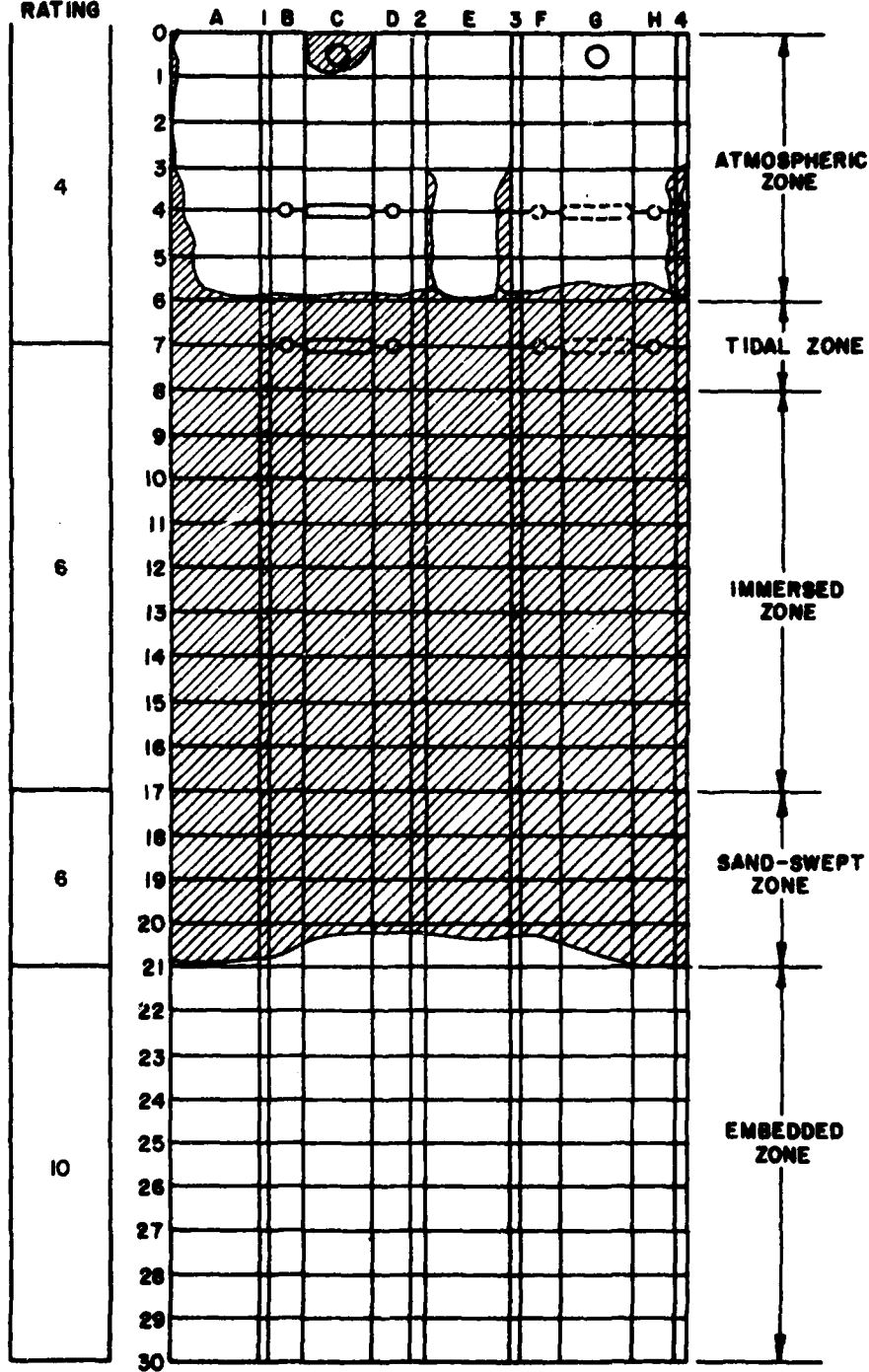
ASTM
RATING



PILE NO. 17B

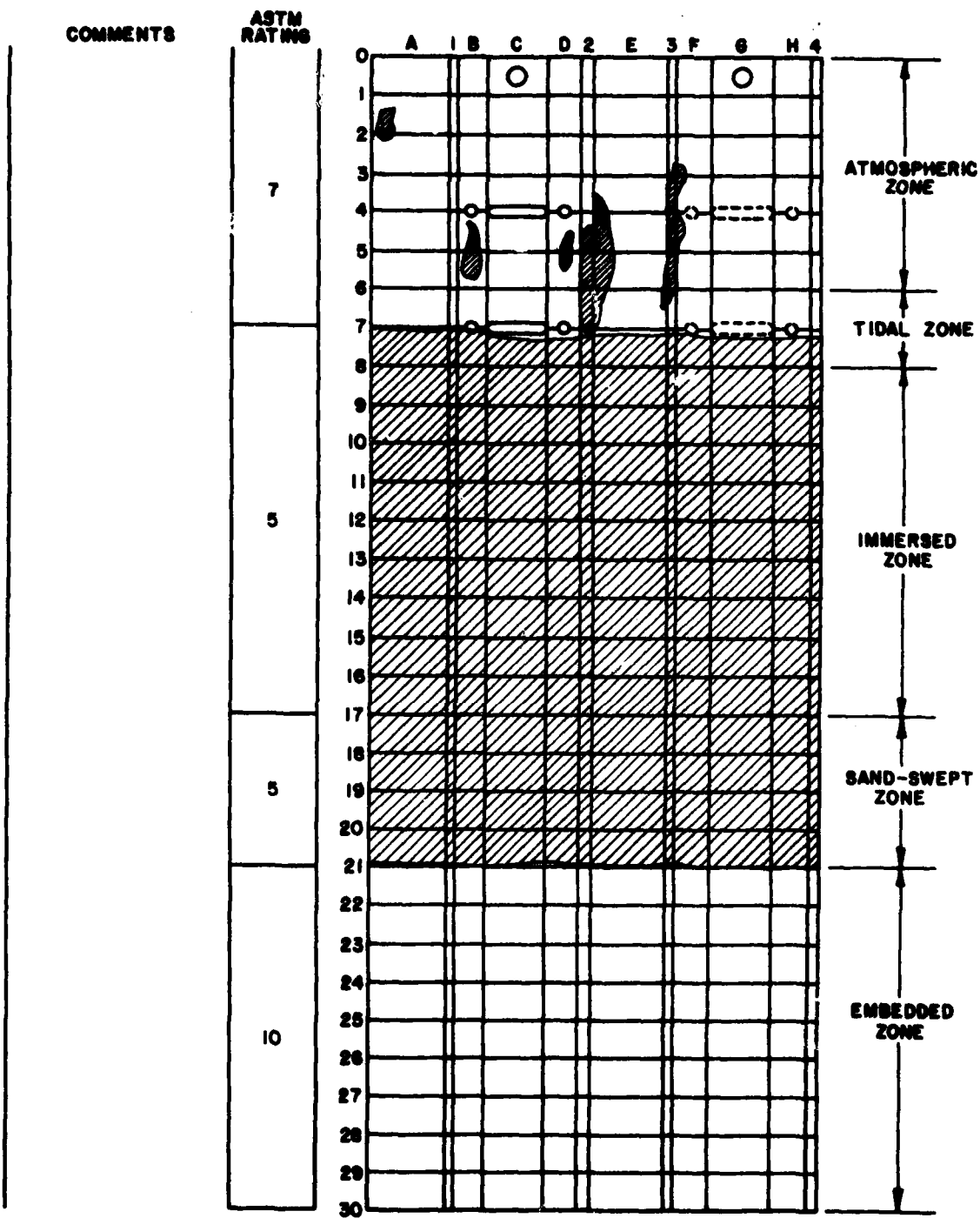
COMMENTS

ASTM
RATING



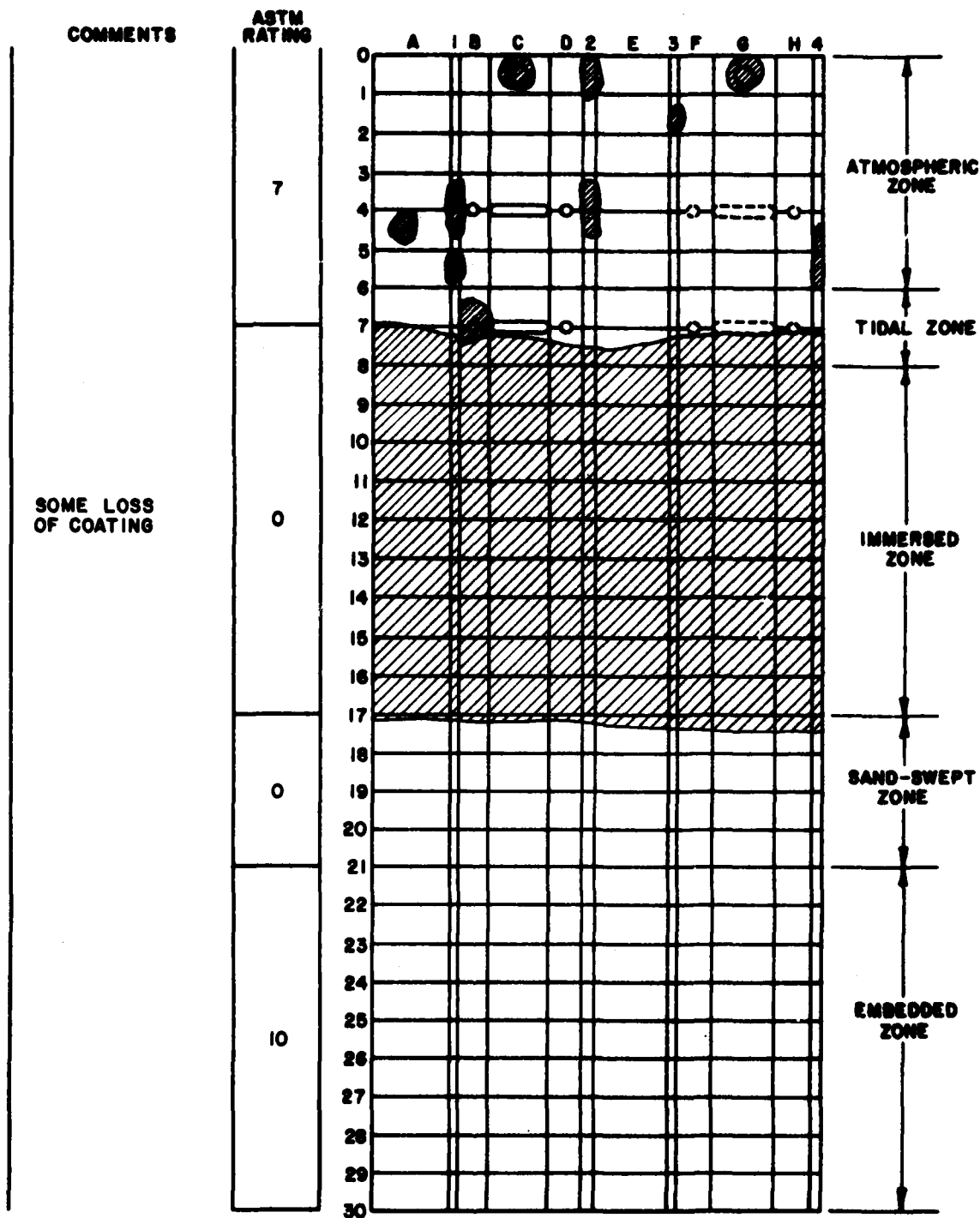
PILE NO. 18A

→ SHOWS RUSTING



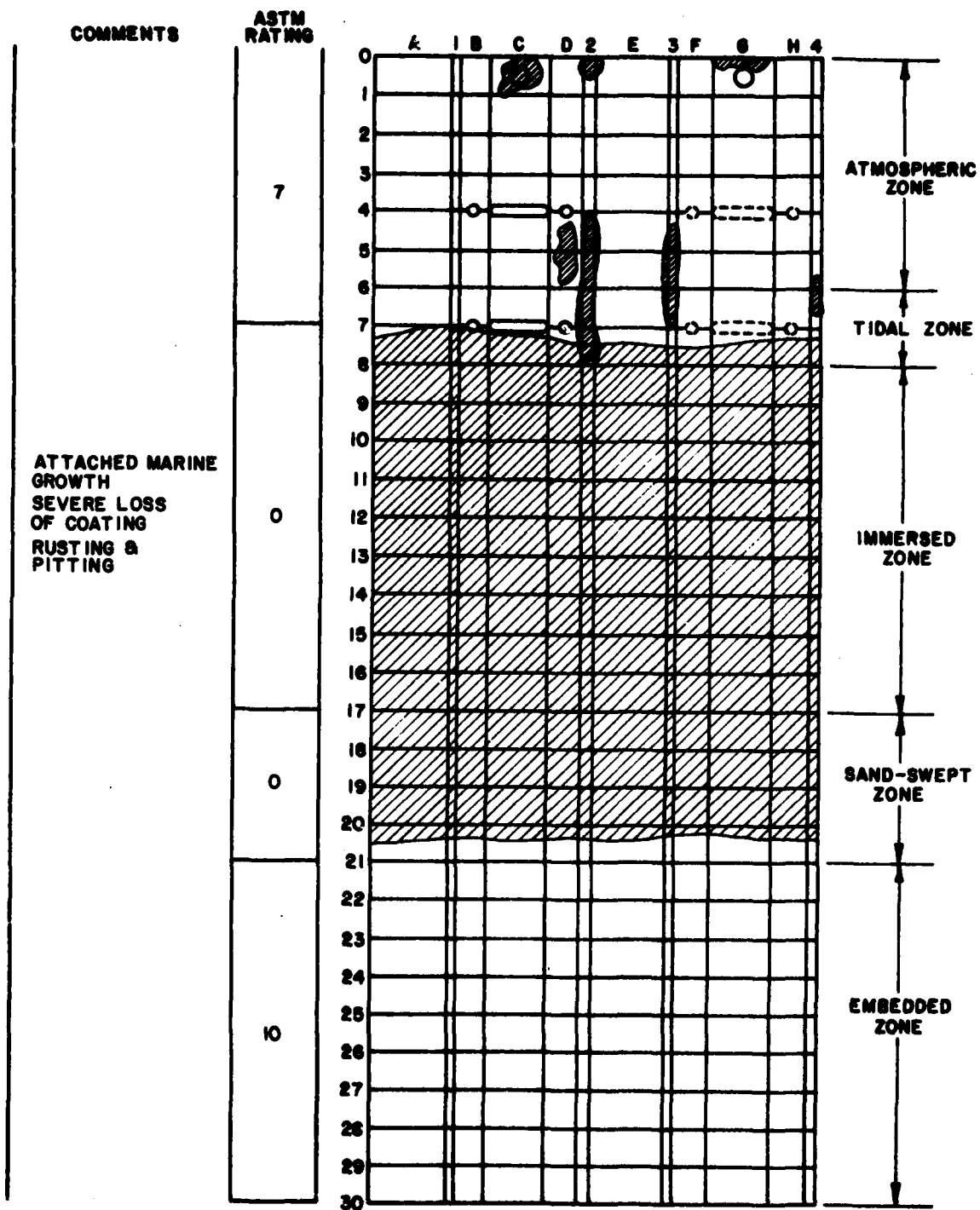
PILE NO. 188

→ SHOWS RUSTING



PILE NO. 19A

→ SHOWS RUSTING

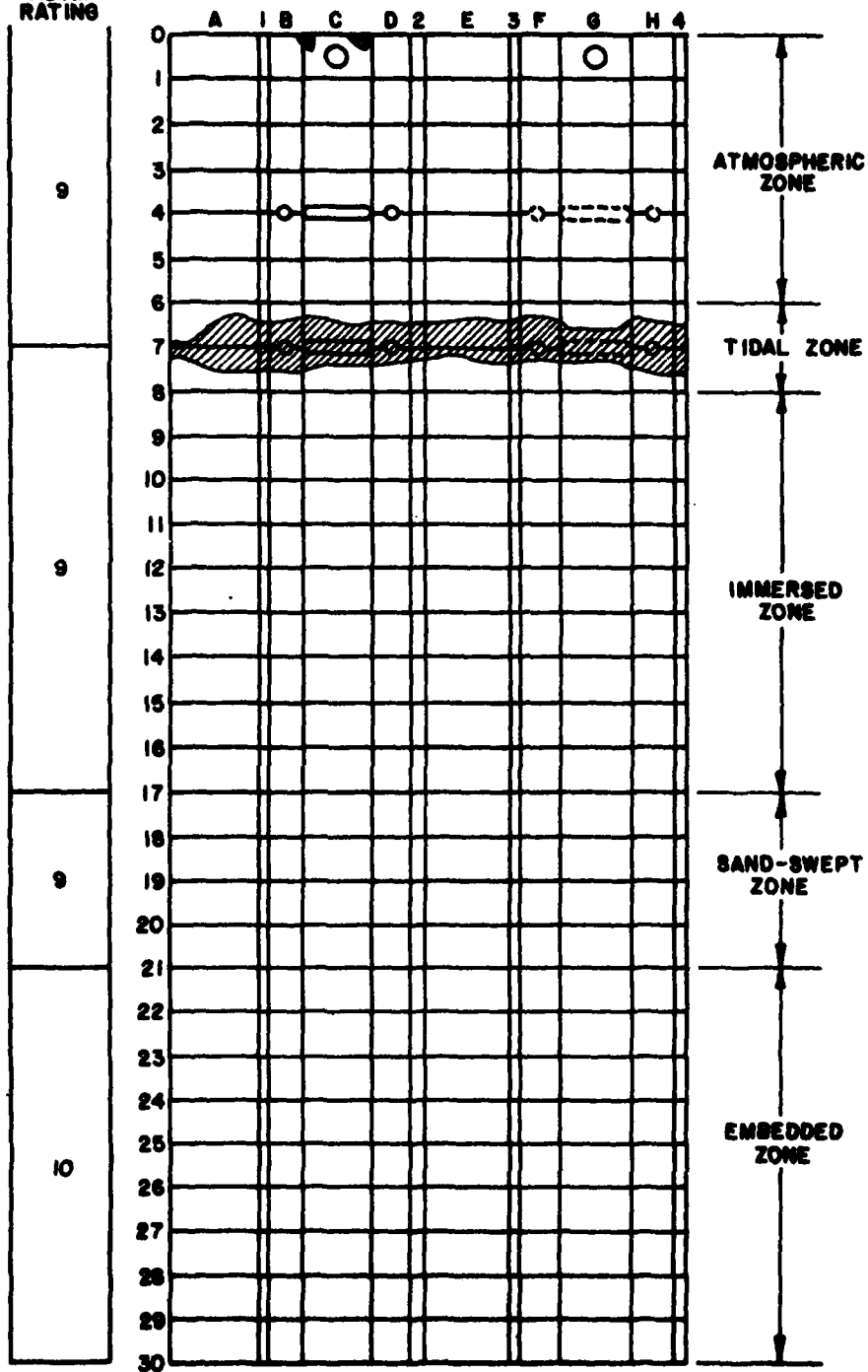


PILE NO. 19B

→ SHOWS RUSTING

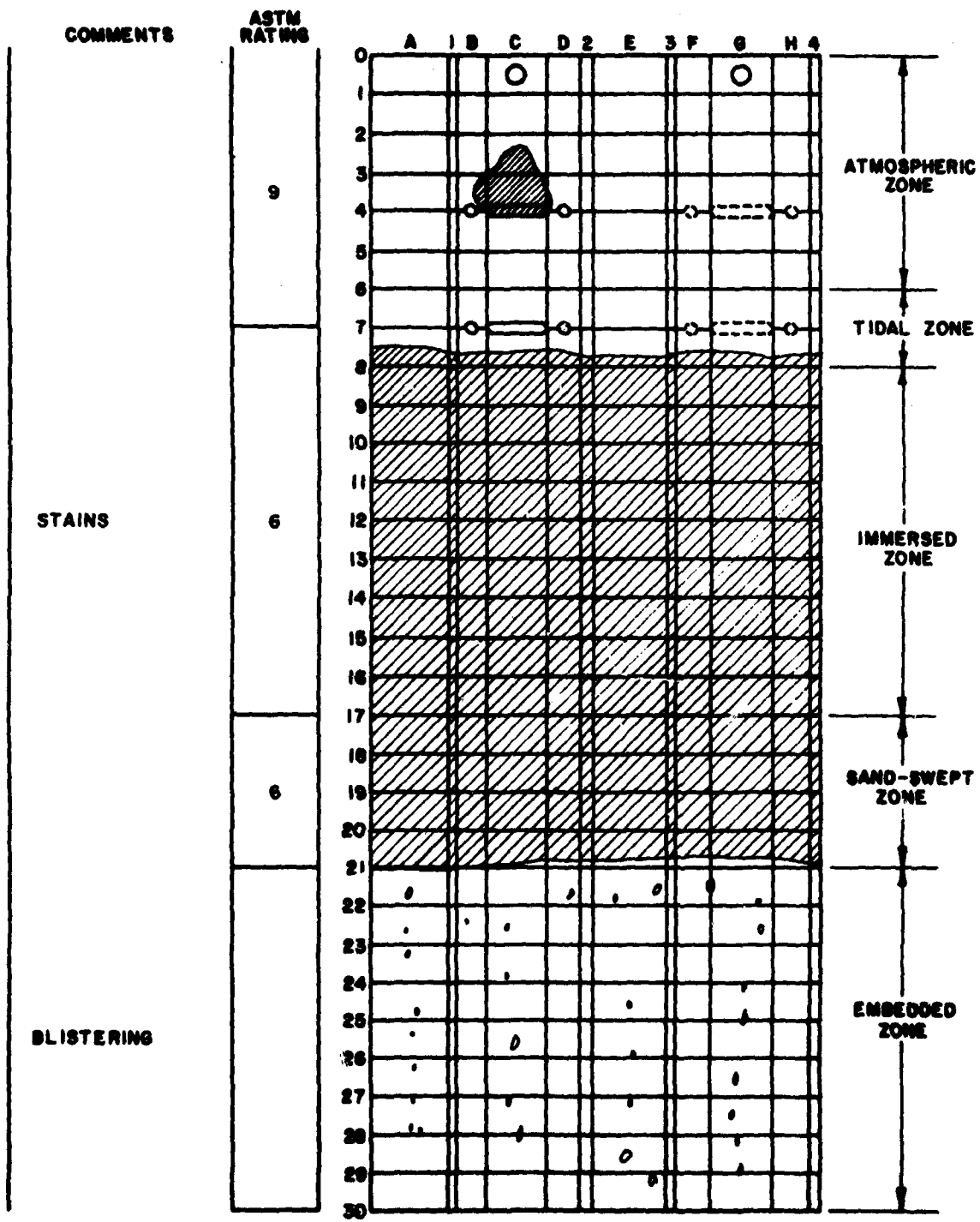
COMMENTS

ASTM
RATING



PILE NO. 20A

 SHOWS RUSTING



PILE NO. 208

→ SHOWS RUSTING

COMMENTS

ASTM
RATING

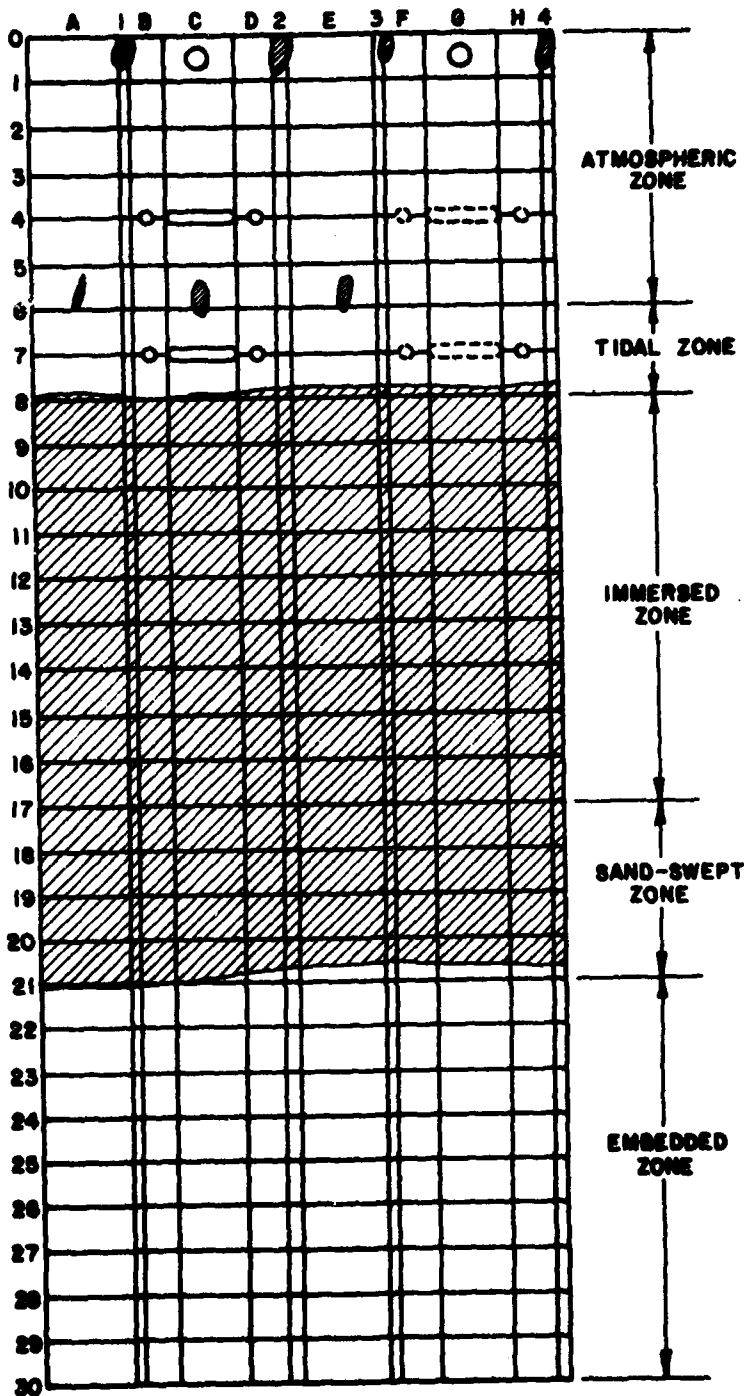
BLISTERS

8

1

1

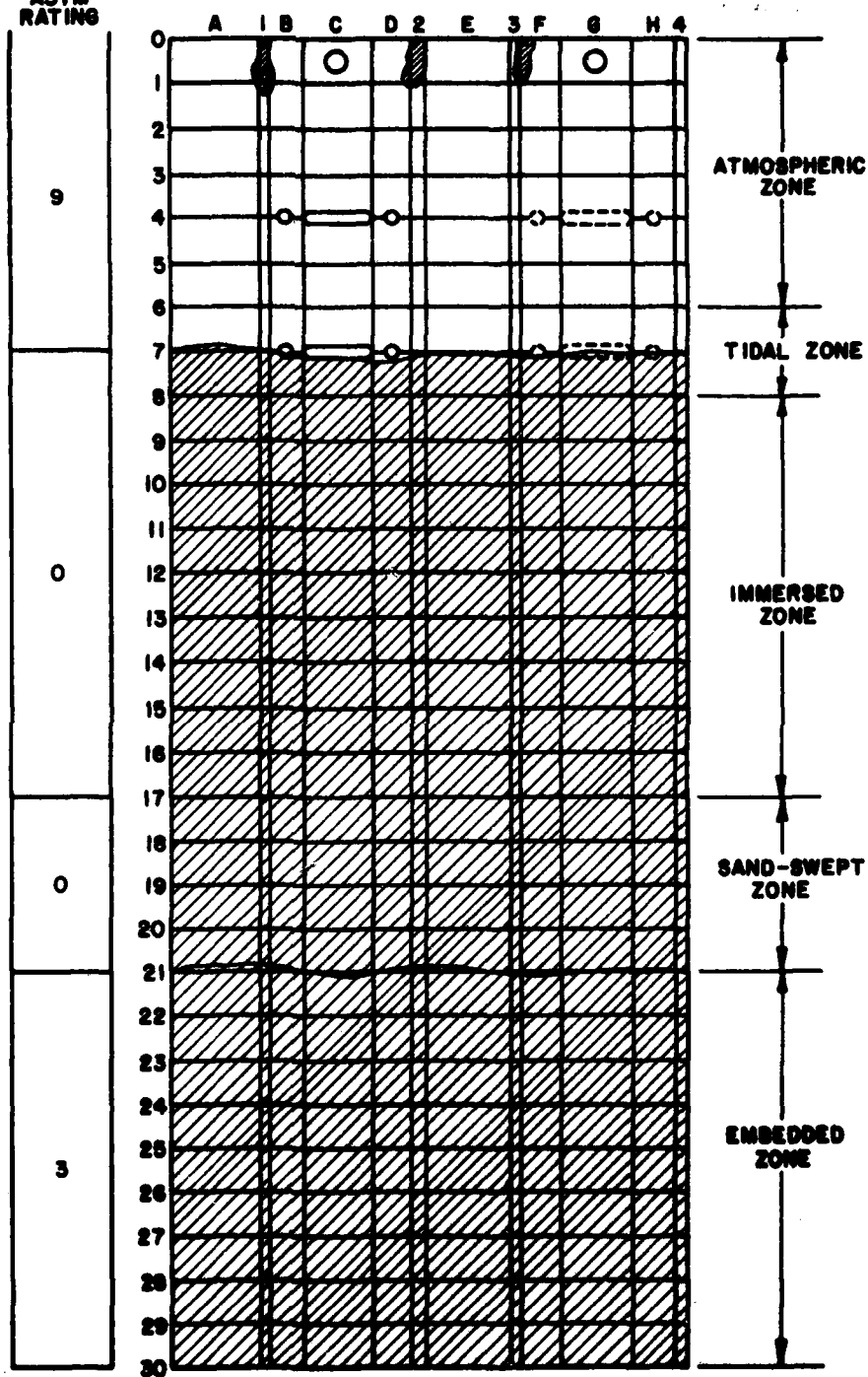
8



COMMENTS

ASTM
RATING

RUST



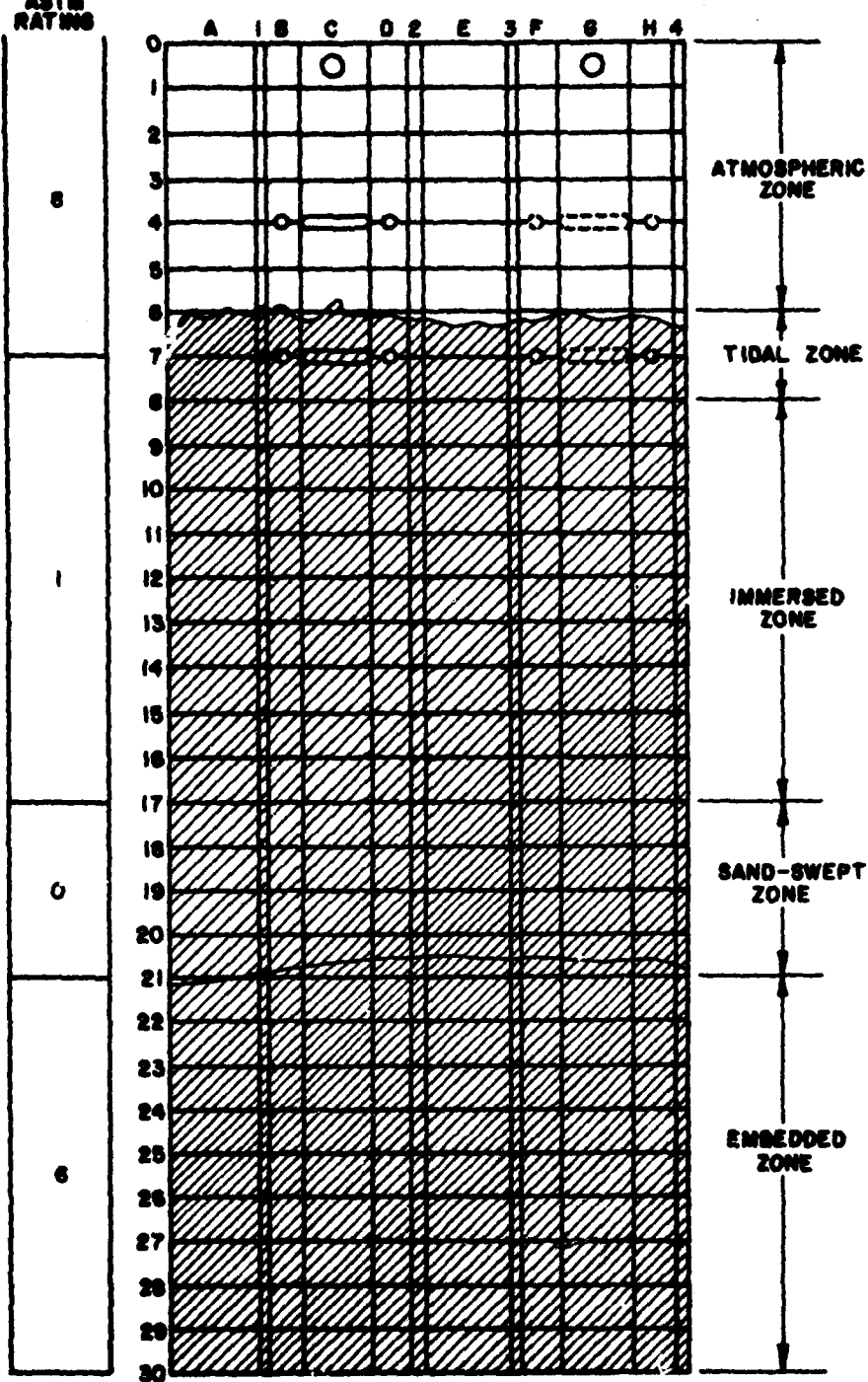
PILE NO. 22A

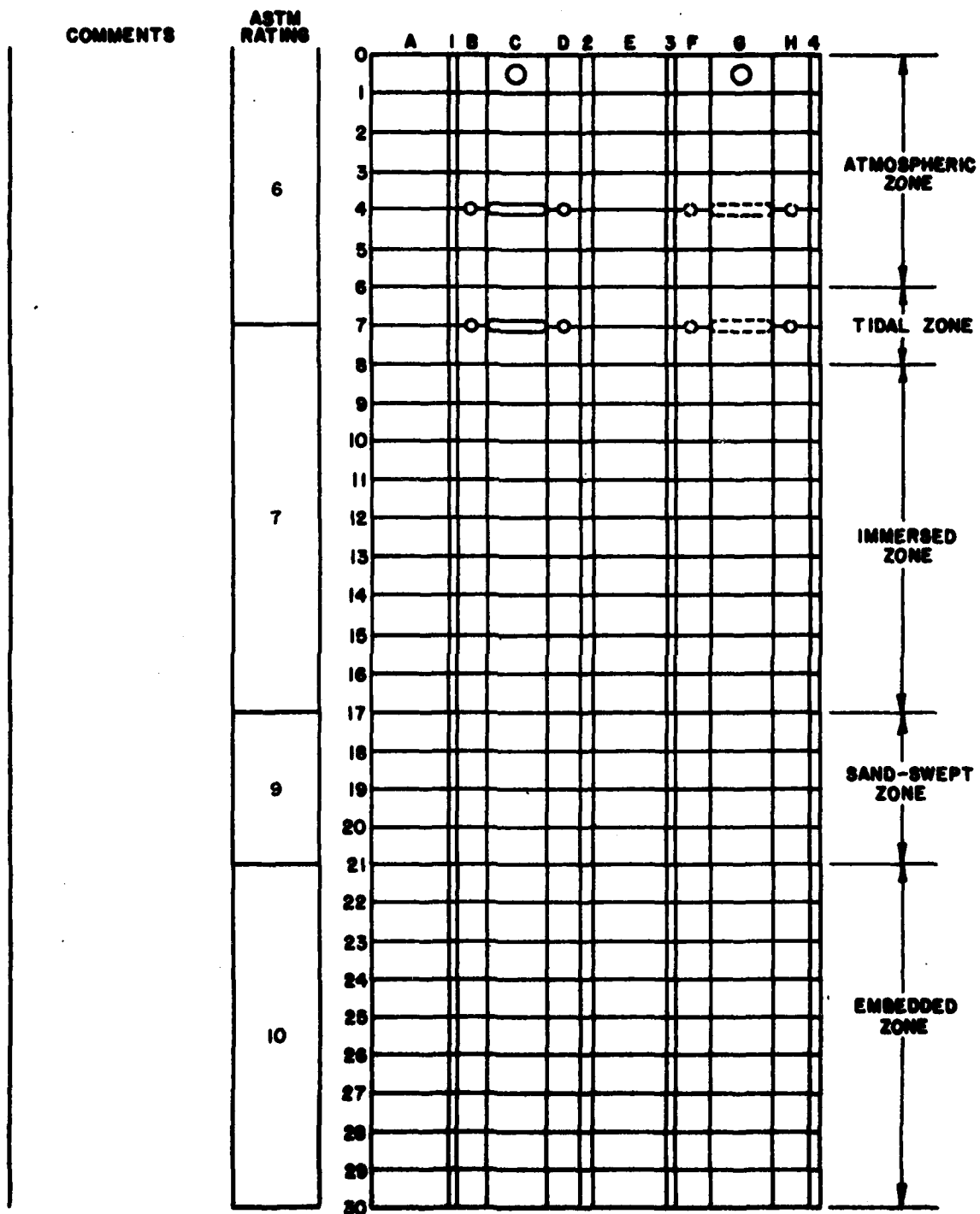
—●— SHOWS RUSTING

COMMENTS

ASTM
RATING

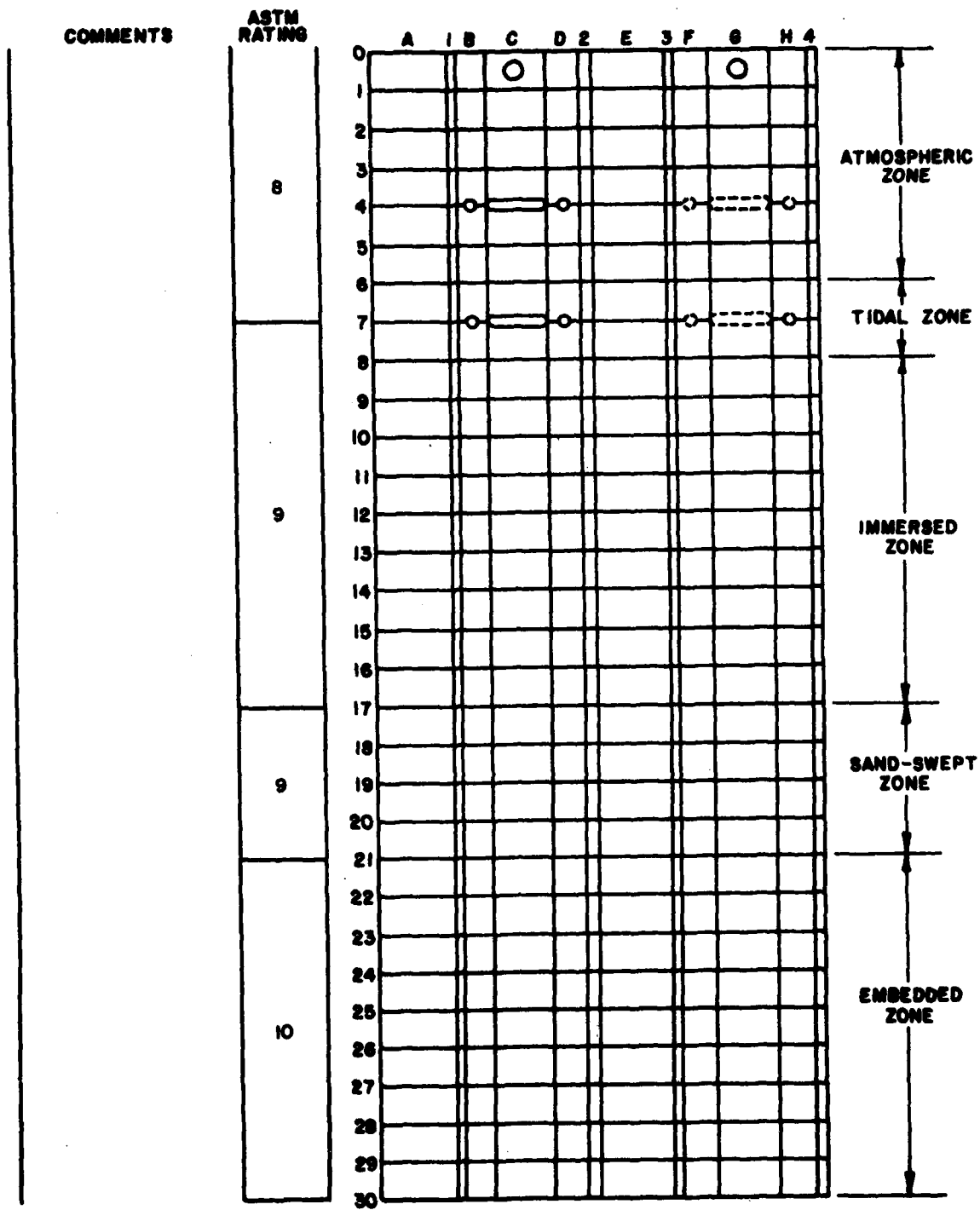
BLISTERING &
STAINING





PILE NO. 28A

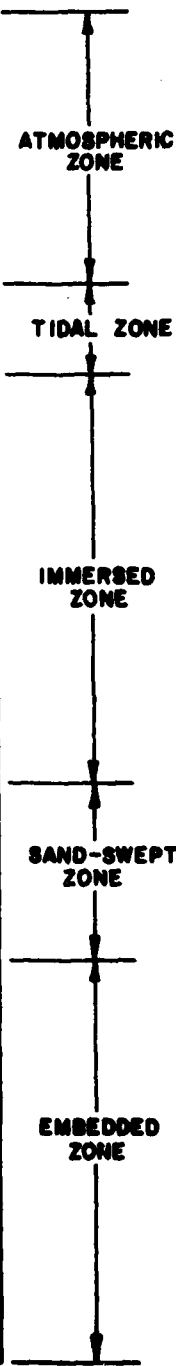
 → SHOWS RUSTING



PILE NO. 27A

→ SHOWS RUSTING

8	
9	
10	



FILE NO. 27B

 SHOWS RUSTING

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Bukowski, John

Coatings and cathodic protection of piling in seawater: results of 10-year exposure at LaCosta Island, FL / by J. Bukowski, A. Kumar -- Champaign, IL : Construction Engineering Research Laboratory ; available from NTIS, 1982. 66 p. (Technical Report ; M-321)

1. LaCosta Island, FL. 2. Steel piling -- corrosion. 3. Seawater corrosion. I. Kumar, Ashok. II. Title. III. Series: Technical Report (Construction Engineering Research Laboratory (U.S.)) ; M-321.

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